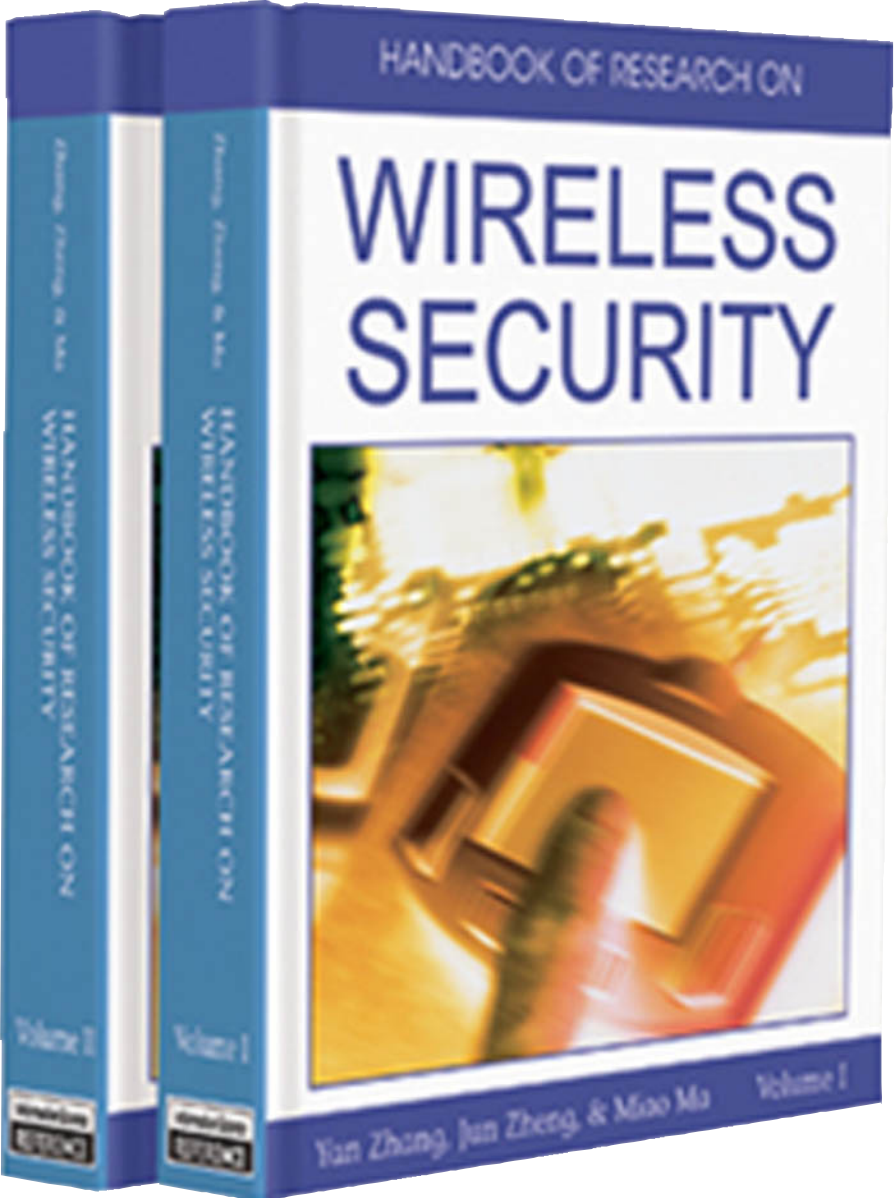
HANDBOOK OF RESEARCH ON
WIRELESS SECURITY
Yan Zhang, Jun Zheng, & Miao Ma
Volume I
Volume II

Handbook of Research on Wireless Security

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Volume I

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to enabling secure and private service discovery in these environments, including the dynamic population of participants, the lack of a universal trust mechanism, and the limited capabilities of the devices. To ensure secure service discovery while addressing privacy issues, trust-based models are inevitable. We survey secure service discovery in the broadband wireless environment. We include case studies of two protocols which include a trust mechanism, and we summarize future research directions.

Chapter III

The recent developments in the mobile technology (mobile phones, middleware, wireless networks, etc.) created a need for new methods of protecting the code transmitted through the network. The oldest and the simplest mechanisms concentrate more on the integrity of the code itself and on the detection of unauthorized manipulation. The newer solutions not only secure the compiled program, but also the data that can be gathered during its "journey," and even the execution state. Some other approaches are based on prevention rather than detection. In the chapter we present a new idea of securing mobile agents. The proposed method protects all components of an agent: the code, the data, and the execution state. The proposal is based on a zero-knowledge proof system and a secure secret sharing scheme, two powerful cryptographic primitives. Next, the chapter includes security analysis of the new method and its comparison to other currently most widespread solutions. Finally, we propose a new direction of securing mobile agents by straightening the methods of protecting integrity of the mobile code with risk analysis and a reputation system that helps avoiding a high-risk behavior.

Chapter IV

The broad aim of identity management (IdM) is to manage the resources of an organization (such as files, records, data and communication infrastructure, and services) and to control and manage access to those resources in an efficient and accurate way. Consequently, identity management is both a technical and process orientated concept. The concept of IdM has begun to be applied in identities related applications in enterprises, governments, and Web services since 2002. As the integration of heterogeneous wireless networks becomes a key issue in towards the next generation (NG) networks, IdM will be crucial to the success of NG wireless networks. A number of issues, such as mobility management, multioperator, and securities require the corresponding solutions in terms of user authentication, access control, and so forth. IdM in NG wireless networks is about managing the digital identity of a user and ensuring that users have fast, reliable, and secure access to distributed resources and services of an NGN and the associated service providers, across multiple systems and business contexts.

Along with other security vulnerabilities, defense against denial-of-service attacks is a critical component of any security system. Unlike in wired networks where denial-of-service attacks have been extensively studied, there is a lack of research for preventing such attacks in wireless networks. In addition to various vulnerabilities, some factors leading to different types of denial-of-service attacks and some defense mechanisms are discussed in this chapter. This can help to better understand the wireless network vulnerabilities and subsequently more techniques and procedures to combat these attacks may be developed by researchers.

Chapter XI

This chapter deals with challenges raised by securing transport, service access, user privacy, and accounting in wireless environments. Key generation, delivery, and revocation possibilities are discussed and recent solutions are shown. Special focus is on efficiency and adaptation to a mobile environment. Device domains in personal area networks and home networks are introduced to provide personal digital rights management (DRM) solutions. The value of smartcards and other security tokens are shown and a secure and convenient transmission method is recommended based on the mobile phone and near field communication technology.

Chapter XII

Architecture and protocols for authentication, authorization, and accounting (AAA) are one of the most important design considerations in 3G/4G telecommunication networks. Many advances have been made to exploit the benefits of the current systems based on the protocol RADIUS, and the evolution to migrate into the more secure, robust, and scalable protocol DIAMETER. DIAMETER is the protocol of choice for the IP multimedia subsystem (IMS) architecture, the core technology for the next generation networks. It is envisioned that DIAMETER will be widely used in various wired and wireless systems to facilitate robust and seamless authentication, authorization, and accounting. In this chapter, we provide an overview of the major AAA protocols of RADIUS and DIAMETER, and we discuss their roles in practical 1xEV-DO network architectures in the three major network tiers: access, distribution, and core. We conclude the chapter with a short summary of the current and future trends related to the DIAMETER-based AAA systems.

Chapter XIII

Converging networks and mobility raise new challenges towards the existing authentication, authorisation, and accounting (AAA) systems. Focus of the research is towards integrated solutions for seamless service access of mobile users. Interworking issues between mobile and wireless networks are the basis for detailed research on handover delay, multidevice roaming, mobile networks, security, ease-of-use, and anonymity of the user. This chapter provides an overview over state-of-the-art in authentication for mobile systems, and suggests extending AAA-mechanisms to home and community networks, taking into account security and privacy of the users.

Chapter XIV

Wireless networks are gaining popularity that comes with the occurrence of several networking technologies raising from personal to wide area, from centralized to distributed, and from infrastructure-based to infrastructure-less. Wireless data link characteristics such as openness of transmission media make these networks vulnerable to a novel set of security attacks, despite those that they inherit from wired networks. In order to ensure the protection of mobile nodes that are interconnected using wireless protocols and standards, it is essential to provide an in-depth study of a set of mechanisms and security models. In this chapter, we present the research studies and proposed solutions related to the authentication, privacy, trust establishment, and management in wireless networks. Moreover, we introduce and discuss the major security models used in a wireless environment.

Chapter XV

In the design and analysis of authentication and key agreement protocols, provable secure formal methods play a very important role, among which the Canetti-Krawczyk(CK) model and the universal composable(UC) security model are very popular at present. This chapter focuses on these two models and consists mainly of three parts. (1) There is an introduction to the CK model and the UC model. (2) There is also a study of these two models, which includes an analysis of the CK model and an extension of the UC security model. The analysis of the CK model presents its security analysis, advantages, and disadvantages, and a bridge between this formal method and the informal method (heuristic method) is established; an extension of the UC security model gives a universally composable anonymous hash certification model. (3) The applications of these two models are also presented. With these two models, the four-way handshake protocols in 802.11i and Chinese WLAN security standard WAPI are analyzed.

Chapter XVI

In a wireless environment, multimedia transmission is often affected by the error rate, delaying, terminal's power or bandwidth, and so forth, which brings difficulties to multimedia content protection. In the past decade, wireless multimedia protection technologies have been attracting more and more researchers. Among them, wireless multimedia encryption and watermarking are two typical topics. Wireless multimedia encryption protects multimedia content's confidentiality in wireless networks, which emphasizes improving the encryption efficiency and channel friendliness. Some means have been proposed, such as the format-independent encryption algorithms that are time efficient compared with traditional ciphers, the partial encryption algorithms that reduce the encrypted data volumes by leaving some information unchanged, the hardware-implemented algorithms that are more efficient than software based ones, the scalable encryption algorithms that are compliant with bandwidth changes, and the robust encryption algorithms that are compliant with error channels. Compared with wireless multimedia encryption, wireless multimedia watermarking is widely used in ownership protection, traitor tracing, content authentication, and so forth. To keep costs low, a mobile agent is used to partition some of the watermarking tasks. To counter transmission errors, some channel encoding methods are proposed to encode the watermark. To keep robust, some means are proposed to embed a watermark into media data of low bit rate. Based on both watermarking and encryption algorithms, some applications arise, such as secure multimedia sharing or secure multimedia distribution. In this chapter, the existing wireless multimedia encryption and watermarking algorithms are summarized according to the functionality and multimedia type, their performances are analyzed and compared, the related applications are presented, and some open issues are proposed.

In this chapter, a system-on-chip design of the newest powerful standard in the hash families, named Whirlpool, is presented. With more details, an architecture and two VLSI implementations are presented. The first implementation is suitable for high-speed applications while the second one is suitable for applications with constrained silicon area resources. The architecture permits a wide variety of implementation tradeoffs. Different implementations have been introduced and each specific application can choose the appropriate speed-area trade-off implementation. The implementations are examined and compared in the security level and in the performance by using hardware terms. Whirlpool with RIPEMD, SHA-1, and SHA-2 hash functions are adopted by the International Organization for Standardization (ISO/IEC) 10118-3 standard. The Whirlpool implementations allow fast execution and effective substitution of any previous hash families' implementations in any cryptography application.

Section II
Security in 3G/B3G/4G

The fourth generation of mobile networks (4G) will be a technology-opportunistic and user-centric system combining the economic and technological advantages of different transmission technologies to provide a context-aware and adaptive service access anywhere and at any time. Security turns out to be one of the major problems that arise at different interfaces when trying to realize such a heterogeneous system by integrating the existing wireless and mobile systems. Indeed, current wireless systems use very different and difficult to combine proprietary security mechanisms, typically relying on the associated user and infrastructure management means. It is generally impossible to apply a security policy to a system consisting of different heterogeneous subsystems. In this chapter, we first briefly present the security of candidate 4G access systems, such as 2/3G, WLAN, WiMax and so forth. In the next step, we discuss the arising security issues of the system interconnection. We namely define a logical access problem in heterogeneous systems and show that both the technology-bound low-layer and the overlaid high-layer access architectures exhibit clear shortcomings. We present and discuss several proposed approaches aimed at achieving an adaptive, scalable, rapid, easy-to-manage, and secure 4G service access independently of the used operator and infrastructure. We then define general requirements on candidate systems to support such 4G security.

Chapter XIX

The integration of heterogeneous mobile/wireless networks using an IP-based core network materializes the beyond 3G (B3G) mobile networks. Along with a variety of new perspectives, the new network model raises new security concerns, mainly because of the complexity of the deployed architecture and the heterogeneity of the employed technologies. In this chapter, we examine and analyze the security architectures and the related security protocols, which are employed in B3G networks focusing on their functionality and the supported security services. The objectives of these protocols are to protect the involved parties and the data exchanged among them. To achieve these, they employ mechanisms that provide mutual authentication as well as ensure the confidentiality and integrity of the data transferred over the wireless interface and specific parts of the core network. Finally, based on the analysis of the security mechanisms, we present a comparison of them that aims at highlighting the deployment advantages of each one and classifies the latter in terms of (a) security, (b) mobility, and (c) reliability.

Chapter XX

This chapter analyzes the security architecture designed for the protection of the universal mobile telecommunication system (UMTS). This architecture is built on the security principles of 2G systems with improvements and enhancements in certain points in order to provide advanced security services. The main objective of the 3G security architecture is to ensure that all information generated by or relating to a user, as well as the resources and services provided by the serving network and the home environment, are adequately protected against misuse or misappropriation. Based on the carried analysis, the critical points of the 3G security architecture, which might cause network and service vulnerability, are

identified. In addition, the current research on the UMTS security and the proposed enhancements that aim at improving the UMTS security architecture are briefly presented and analyzed.

Chapter XXI

Motivated by the requirements for higher data rate, richer multimedia services, and broader radio range, wireless mobile networks are currently in the stage evolving from the second-generation (2G), for example, global system for mobile communications (GSM), into the era of third-generation (3G) or beyond 3G or fourth-generation (4G). Universal mobile telecommunications system (UMTS) is the natural successor of the current popular GSM. Code division multiple access 2000 (CDMA2000) is the next generation version for the CDMA-95, which is predominantly deployed in the North America and North Korea. Time division-sychrononous CDMA (TD-SCDMA) is in the framework of 3GPP2 and is expected to be one of the principle wireless technologies employed in China in the future. It is envisioned that each of three standards in the framework of international mobile telecommunications-2000 (IMT-2000) will play a significant role in the future due to the backward compatibility, investment, maintenance cost, and even politics. In all of the potential standards, access security is one of the primary demands as well as challenges to resolve the deficiency existing in the second generation wireless mobile networks such as GSM, in which only one-way authentication is performed for the core network part to verify the user equipment (UE). Such access security may lead to the "man-in-middle" problem, which is a type of attack that can take place when two clients that are communicating remotely exchange public keys in order to initialize secure communications. If both of the public keys are intercepted in the route by someone, that someone can act as a conduit and send in the messages with a fake public key. As a result, the secure communication is eavesdropped on by a third party.

Chapter XXII

The global system for mobile communications (GSM) is the most popular standard that implements second generation (2G) cellular systems. 2G systems combined with general packet radio services (GPRS) are often described as 2.5G, that is, a technology between the 2G and third (3G) generation of mobile systems. GPRS is a service that provides packet radio access for GSM users. This chapter presents the security architecture employed in 2.5G mobile systems, focusing on GPRS. More specifically, the security measures applied to protect the mobile users, the radio access network, the fixed part of the network, and the related data of GPRS, are presented and analyzed in details. This analysis reveals the security weaknesses of the applied measures that may lead to the realization of security attacks by adversaries. These attacks threaten network operation and data transfer through it, compromising end-users and network

security. To defeat the identified risks, current research activities on the GPRS security propose a set of security improvements to the existing GPRS security architecture.

Chapter XXIII

Security measures of mobile infrastructures have always been important from the early days of the creation of cellular networks. Nowadays, however, the traditional security schemes require a more fundamental approach to cover the entire path from the mobile user to the server. This fundamental approach is so-called end-to-end (E2E) security coverage. The main focus of this chapter is to discuss such architectures for IEEE 802.16e (Mobile-WiMAX) and major 3G cellular networks. The end-to-end implementations usually contain a complete set of algorithms and protocol enhancements (e.g., mutual identification, authentications, and authorization), including the VLSI implementations. This chapter discusses various proposals at the protocol level.

Chapter XXIV

This chapter outlines how cellular authentication can be utilized for generic application security. It describes the basic concept of the generic bootstrapping architecture that was defined by the 3rd generation partnership project (3GPP) for current networks and outlines the latest developments for future networks.The chapter will provide an overview of the latest technology trends in the area of generic application security.

Chapter XXV

Network mobility (NEMO) enables seamless and ubiquitous Internet access while on board vehicles. Even though the Internet Engineering Task Force (IETF) has standardized the NEMO basic support protocol as a network layer mobility solution, few studies have been conducted in the area of the authentication, authorization, and accounting (AAA) framework that is a key technology for successful deployment. In this chapter, we first review the existing AAA protocols and analyze their suitability in NEMO environments. After that, we propose a localized AAA framework to retain the mobility transparency as the NEMO basic support protocol and to reduce the signaling cost incurred in the AAA procedures. The proposed AAA framework supports mutual authentication and prevents various threats such as replay

attack, man-in-the-middle attack, and key exposure. Performance analysis on the AAA signaling cost is carried out. Numerical results demonstrate that the proposed AAA framework is efficient under different NEMO environments.

Section III
Security in Ad Hoc and Sensor Networks

Mobile ad hoc network (MANET) is a self-configuring and self-maintaining network characterized by dynamic topology, absence of infrastructure, and limited resources. These characteristics introduce security vulnerabilities, as well as difficulty in providing security services to MANETs. To date, tremendous research has been done to develop security approaches for MANETs. This work will discuss the existing approaches that have intended to defend against various attacks at different layers. Open challenges are also discussed in the chapter.

Providing privacy is often considered a keystone factor for the ultimate take up and success of mobile ad hoc networking. Privacy can best be protected by enabling anonymous communication and, therefore, this chapter surveys existing anonymous communication mechanisms for mobile ad hoc networks. On the basis of the survey, we conclude that many open research challenges remain regarding anonymity provisioning in mobile ad hoc networks. Finally, we also discuss the notorious Sybil attack in the context of anonymous communication and mobile ad hoc networks.

The pervasiveness of wireless communication recently gave mobile ad hoc networks (MANET) significant researchers' attention, due to its innate capabilities of instant communication in many time and mission critical applications. However, its natural advantages of networking in civilian and military environments make it vulnerable to security threats. Support for anonymity in MANET is orthogonal to a critical security challenge we faced in this chapter. We propose a new anonymous authentication protocol for mobile ad hoc networks enhanced with a distributed reputation system. The main objective is to provide mechanisms concealing a real identity of communicating nodes with an ability of resistance

to known attacks. The distributed reputation system is incorporated for a trust management and malicious behavior detection in the network.

Chapter XXIX

The increasing diffusion of wireless portable devices and the emergence of mobile ad hoc networks promote anytime and anywhere opportunistic resource sharing. However, the fear of exposure to risky interactions is currently limiting the widespread uptake of ad hoc collaborations. This chapter introduces to the challenge of identifying and validating novel security models/systems for securing ad hoc collaborations by taking into account the high unpredictability, heterogeneity, and dynamicity of envisioned wireless environments. We claim that the concept of trust management should become a primary engineering design principle, to associate with the subsequent trust refinement into effective authorization policies, thus calling for original and innovative access control models. The chapter overviews the state-of-the-art solutions for trust management and access control in wireless environments, by pointing out both the need for their tight integration and the related emerging design guidelines (e.g., exploitation of context awareness and adoption of semantic technologies).

Chapter XXX

Security has become a primary concern in mobile ad hoc networks (MANETs). The characteristics of MANETs pose both challenges and opportunities in achieving security goals, such as confidentiality, authentication, integrity, availability, access control, and nonrepudiation. Cryptographic techniques are widely used for secure communications in wired and wireless networks. Most cryptographic mechanisms, such as symmetric and asymmetric cryptography, often involve the use of cryptographic keys. However, all cryptographic techniques will be ineffective if the key management is weak. Key management is also a central component in MANET security. The purpose of key management is to provide secure procedures for handling cryptographic keying materials. The tasks of key management include key generation, key distribution, and key maintenance. Key maintenance includes the procedures for key storage, key update, key revocation, key archiving, and so forth. In MANETs, the computational load and complexity for key management are strongly subject to restriction by the node's available resources and the dynamic nature of network topology. A number of key management schemes have been proposed for MANETs. In this chapter, we present a survey of the research work on key management in MANETs according to recent literature.

which is a novel problem. Issues in intrusion detection in ad hoc networks are addressed by numerous research proposals in literature. In this chapter, we first enumerate the properties of ad hoc networks which hinder intrusion detection systems. Second, significant intrusion detection system (IDS) architectures and methodologies proposed in the literature are elucidated. Strengths and weaknesses of these works are then studied and explained. Finally, the future directions, which will lead to the successful deployment of intrusion detection in ad hoc networks, are discussed.

In this chapter we present the growing challenges related to security in wireless sensor networks. We show possible attack scenarios and evidence the ease of perpetrating several types of attacks due to the extreme resource limitations that wireless sensor networks are subjected to. Nevertheless, we show that security is a feasible goal in this resource-limited environment. To prove that security is possible we survey several proposed sensor network security protocols targeted to different layers in the protocol stack. The work surveyed in this chapter enable several protection mechanisms vs. well documented network attacks. Finally, we summarize the work that has been done in the area and present a series of ongoing challenges for future work.

The applications of wireless sensor networks (WSNs) are continuously expanding. Recently, consistent research and development activities have been associated to this field. Security ranks at the top of the issues that should be discussed when deploying a WSN. This is basically due to the fact that WSNs are, by nature, mission-critical. Their applications mainly include battlefield control, emergency response (when a natural disaster occurs), and healthcare. This chapter reviews recent research results in the field of WSN security.

Since routing is a fundamental operation in all types of networks, ensuring routing security is a necessary requirement to guarantee the success of routing operations. A securing routing task gets more challenging as the target network lacks an infrastructure-based routing operation. This infrastructure-less nature that invites a multihop routing operation is one of the main features of wireless sensor networks that raises the importance of secure routing problem in these networks. Moreover, the risky environment, application

criticality, and resources limitations and scarcity exhibited by wireless sensor networks make the task of secure routing much more challenging. All these factors motivate researchers to find novel solutions and approaches that would be different from the usual approaches adopted in other types of networks. The purpose of this chapter is to provide a comprehensive treatment of the routing security problem in wireless sensor networks. The discussion flow of the problem in this chapter begins with an overview on wireless sensor networks that focuses on routing aspects to indicate the special characteristics of wireless sensor networks from routing perspective. The chapter then introduces the problem of secure routing in wireless sensor networks and illustrates how crucial the problem is to different networking aspects. This is followed by a detailed analysis of routing threats and attacks that are more specific to routing operations in wireless sensor networks. A research-guiding approach is then presented to the reader that analyzes and criticizes different techniques and solution directions for the secure routing problem in wireless sensor networks. This is supported by state-of-the-art and familiar examples from the literature. The chapter finally concludes with a summary and future research directions in this field.

Localization of sensor nodes is very important for many applications proposed for wireless sensor networks (WSN), such as environment monitoring, geographical routing, and target tracking. Because sensor networks may be deployed in hostile environments, localization approaches can be compromised by many malicious attacks. The adversaries can broadcast corrupted location information and they can jam or modify the transmitting signals between sensors to mislead them to obtain incorrect distance measurements or nonexistent connectivity links. All these malicious attacks will cause sensors to not be able to, or wrongly, estimate their locations. In this chapter, we summarize the threat models and provide a comprehensive survey and taxonomy of existing secure localization and verification schemes for wireless sensor networks.

One of severe security threats in wireless sensor network is false data injection attack, that is, the compromised sensors forge the events that do not occur. To defend against false data injection attacks, six en-route filtering schemes in a homogeneous sensor network are described. Furthermore, a one sink filtering scheme in a heterogeneous sensor network is also presented. We find that deploying heterogeneous nodes in a sensor network is an attractive approach because of its potential to increase network lifetime, reliability, and resiliency.

Weiser envisioned ubiquitous computing with computing and communicating entities woven into the fabrics of every day life. This chapter deals with the survivability of ambient resource-constrained wireless computing nodes, from fixed sensor network nodes to small devices carried out by roaming entities, for example, as part of a personal area network of a moving person. First, we review the assets that need to be protected, especially the energy of these unplugged devices. There are also a number of specific attacks that are described; for example, direct physical attacks are facilitated by the disappearing security perimeter. Finally, we survey the protection mechanisms that have been proposed with an emphasis on cryptographic keying material and trust management.

Fault tolerance is one of the premier system design desiderata in wireless ad hoc and sensor networks. It is crucial to have a certain level of fault tolerance in most ad hoc and sensor applications, especially for those used in surveillance, security, and disaster relief. In addition, several network security schemes require that the underlying topology provide fault tolerance. In this chapter, we will review various fault tolerant techniques used in topology design for ad hoc and sensor networks, including those for power control, topology control, and sensor coverage.

Section IV
Security in Wireless PAN/LAN/MAN Networks

Security is always an important factor in wireless connections. As with all other existing radio technologies, the Bluetooth standard is often cited to suffer from various vulnerabilities and security inefficiencies, while attempting to optimize the trade-off between performance and complementary services including security. On the other hand, security protocols like IP secure (IPsec) and secure shell (SSH) provide strong, flexible, low cost, and easy to implement solutions for exchanging data over insecure communication links. However, the employment of such robust security mechanisms in wireless realms enjoins additional research efforts due to several limitations of the radio-based connections, for example link bandwidth and unreliability. This chapter will evaluate several Bluetooth personal area network (PAN) parameters, including absolute transfer times, link capacity, throughput, and goodput. Experiments shall employ both Bluetooth native security mechanisms, as well as the two aforementioned protocols. Through a plethora of scenarios, utilizing both laptops and palmtops, we offer a comprehensive in-depth comparative analysis of each of the aforementioned security mechanisms when deployed over Bluetooth communication links.

study on fast authentication solutions found in the literature as well as the industry that address this problem. These proposals focus on solving the mentioned problem for intradomain handoff scenarios where the access points belong to the same administrative domain or provider. Interdomain roaming is also becoming common-place for wireless access. We need fast authentication solutions for these environments that are managed by independent administrative authorities. We detail such a solution that explores the use of local trust relationships to foster fast authentication.

Mass deployment of radio-frequency identification (RFID) technology is now becoming feasible for a wide variety of applications ranging from medical to supply chain and retail environments. Its main draw-back until recently was high production costs, which are now becoming lower and acceptable. But due to inherent constraints of RFID technology (in terms of limited power and computational resources) these devices are the subject of intensive research on how to support and improve increasing demands for security and privacy. This chapter therefore focuses on security and privacy issues by giving a general overview of the field, the principles, the current state of the art, and future trends. An improvement in the field of security and privacy solutions for this kind of wireless communications is described as well.

Wireless communications are becoming ubiquitous in homes, offices, and enterprises with the popular IEEE 802.11 wireless LAN technology and the up-and-coming IEEE 802.16 wireless MAN technology. The wireless nature of communications defined in these standards makes it possible for an attacker to snoop on confidential communications or modify them to gain access to home or enterprise networks much more easily than with wired networks. Wireless devices generally try to reduce computation overhead to conserve power and communication overhead to conserve spectrum and battery power. Due to these considerations, the original security designs in wireless LANs and MANs used smaller keys, weak message integrity protocols, weak or one-way authentication protocols, and so forth. As wireless networks became popular, the security threats were also highlighted to caution users. A security protocol redesign followed first in wireless LANs and then in wireless MANs. This chapter discusses the security threats and requirements in wireless LANs and wireless MANs, with a discussion on what the original designs missed and how they were corrected in the new protocols. It highlights the features of the current wireless LAN and MAN security protocols and explains the caveats and discusses open issues. Our aim is to provide the reader with a single source of information on security threats and requirements, authentication technologies, security encapsulation, and key management protocols relevant to wireless LANs and MANs.

An overview of the technical and business aspects is given for the corporate deployment of services over WiMAX. WiMAX is considered to be a strong candidate for the next generation of broadband wireless access; therefore its security is critical. This chapter provides an overview of the inherent and complementary benefits of broadband deployment over a long haul wireless pipe, such as WiMAX. In addition, we explore end-to-end (E2E) security structures necessary to launch secure business and consumer class services. The main focus of this chapter is to look for the best security practice to achieve E2E security in both vertical and horizontal markets. The E2E security practices will ensure complete coverage of the entire link from the client (user) to the server. This is also applicable to wireless virtual private network (VPN) applications where the tunneling mechanism between the client and the server ensures complete privacy and security for all users. The same idea for E2E security is applied to client-server-based multimedia applications, such as in IP multimedia subsystem (IMS) and voice over IP (VoIP), where secure client/server communication is required. In general, we believe that WiMAX provides the opportunity for a new class of high data rate symmetric services. Such services will require E2E security schemes to ensure risk-free high data-rate uploads and downloads of multimedia applications. WiMAX provides the capability for embedded security functions through the 802.16 security architecture standards. IEEE 802.16 is further subcategorized as 802.16d (fixed-WiMAX) and 802.16e (mobile-WiMAX). Due to the mobility and roaming capabilities in 802.16e and the fact that the medium of signal transmission is accessible to everyone, there are a few extra security considerations applied to 802.16e. These extra features include PKMv2, PKM-EAP authentication method, AES encryption wrapping, and so forth. The common security features of 802.16d and 802.16e are discussed in this chapter, as well as the highlights of the security comparisons between other broadband access, 3G technologies, and WiMAX.

During the last few years, mobile broadband access has been a popular concept in the context of fourth generation (4G) cellular systems. After the wide acceptance and deployment of the wired broadband connections, such as DSL, the research community in conjunction with the industry have tried to develop and deploy viable mobile architectures for broadband connectivity. The dominant architectures which have already been proposed are Wi-Fi, UMTS, WiMax, and flash-OFDM. In this chapter, we analyze these protocols with respect to their security mechanisms. First, a detailed description of the authentication, confidentiality, and integrity mechanisms is provided in order to highlight the major security gaps and threats. Subsequently, each threat is evaluated based on three factors: likelihood, impact, and risk.

Preface

Wireless networks have been seen unprecedented growth in the past few years. Wireless technologies provide users with a variety of benefits like portability, flexibility, increased productivity, and lower installation costs. Various wireless technologies, from wireless local area network (WLAN) and Bluetooth to WiMAX and third generation (3G) have been developed. Each of these technologies has its own unique applications and characteristics. For example, a WLAN can provide the wireless users with high bandwidth data communication in a restricted and dense area (hotpot). Ad hoc networks, like those enabled by Bluetooth, allow data synchronization with network systems and application sharing between devices. WiMAX can provide high-speed, high bandwidth efficiency, and high-capacity multimedia services for residential as well as enterprise applications.

However, any wireless technology is inherently risky. It has the same risks as the wired networks as well as new risks brought by the wireless connectivity. There have been many reports of security weaknesses and problems related to different wireless technologies, which make wireless security quite a hot research topic recently, both in the academia and industry.

Wireless security is a very broad area as there are so many different wireless technologies existing. Each wireless technology has its own architecture, algorithms, and protocols. Different wireless technologies have their own application areas and different security concerns, requirements, and solutions. To this end, we want to bring up the *Handbook of Research on Wireless Security* to serve as a single comprehensive reference in the field of wireless security.

In this book, the basic concepts, terms, protocols, systems, architectures, and case studies in the wireless security are provided. It identifies the fundamental problems, key challenges, and future directions in designing secure wireless systems. It covers a wide spectrum of topics in a variety of wireless networks, including attacks, secure routing, encryption, decryption, confidentiality, integrity, key management, identity management, and also security protocols in standards.

The chapters of this book are authoritatively contributed by a group of internationally renowned experts on wireless security. They are organized in four sections:

- Section I: Security Fundamentals
- Section II: Security in 3G/B3G/4G
- Section III: Security in Ad Hoc and Sensor Networks
- Section IV: Security in Wireless PAN/LAN/MAN

Section I introduces the basic concepts and fundamental mechanisms of wireless security. This section is able to provide the necessary background for readers and introduce all the fundamental issues on wireless security without previous knowledge on this area. Section II discusses all the security aspects in 3G/B3G/4G. It is well known that 3G mobile systems offer mobile users content rich services, wire-

less broadband access to Internet, and worldwide roaming. Future 4G mobile communication networks are expected to provide all IP-based services for heterogeneous wireless access technologies, assisted by mobile IP to provide seamless Internet access for mobile users. However the broadcast nature of the wireless communication and increased popularity of wireless devices introduce serious security vulnerabilities. A variety of security issues regarding 3G/B3g/4G will be introduced and addressed with effective solutions (e.g., identity management, confidentiality and integrity mechanisms, evaluation of the current 3G/B3G/4G security protocols, analysis of the impact of security deployment upon the network performance, etc.). Section III explores the security in ad hoc and sensor networks. In recent years, tremendous technological advances have been made in the areas of wireless ad hoc and sensor networks. Such networks have a significant impact on a variety of applications including scientific, military, medical, industrial, office, home, and personal domains. However, these networks introduce new security challenges due to their dynamic topology, severe resource constraints, and absence of a trusted infrastructure. Many aspects of security issues regarding the ad hoc and sensor networks will be covered, including key management, cryptographic protocols, authentication and access control, intrusion detection and tolerance, secure location services, privacy and anonymity, secure routing, resilience against different types of attacks, and so forth. Section IV exploits the security problems in wireless PAN/LAN/MAN. Nowadays we have continuously growing markets for the wireless PANs, wireless LANs, and wireless MANs, but there is a big black hole in the security of this kind of network. Diverse aspects of the security issues on these types of networks will be introduced. For instance, the threats and vulnerabilities in wireless LANs, access control in wireless LANs, evaluating security mechanisms in wireless PANs, the protocols and mechanisms to enhance the security of wireless LANs/MANs, security issues in WiMAX, and so forth are discussed. Practical examples will also be introduced to enhance the understanding.

This book can serve as an essential and useful reference for undergraduate and graduate students, educators, scientists, researchers, engineers, and research strategists in the field of wireless security.

We hope that by reading this book the reader can not only learn the basic concepts of wireless security but also get a good insight into some of the key research works in securing the wireless networks. Our goal is to provide an informed and detailed snapshot of this fast moving field. If you have any feedback or suggestion, please contact the editors.

Yan Zhang, Jun Zheng, and Miao Ma

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Section I
Security Fundamentals

Chapter I
Malicious Software in Mobile Devices

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ABSTRACT

This chapter examines the scope of malicious software (malware) threats to mobile devices. The stakes for the wireless industry are high. While malware is rampant among 1 billion PCs, approximately twice as many mobile users currently enjoy a malware-free experience. However, since the appearance of the Cabir worm in 2004, malware for mobile devices has evolved relatively quickly, targeted mostly at the popular Symbian smartphone platform. Significant highlights in malware evolution are pointed out that suggest that mobile devices are attracting more sophisticated malware attacks. Fortunately, a range of host-based and network-based defenses have been developed from decades of experience with PC malware. Activities are underway to improve protection of mobile devices before the malware problem becomes catastrophic, but developers are limited by the capabilities of handheld devices.

INTRODUCTION

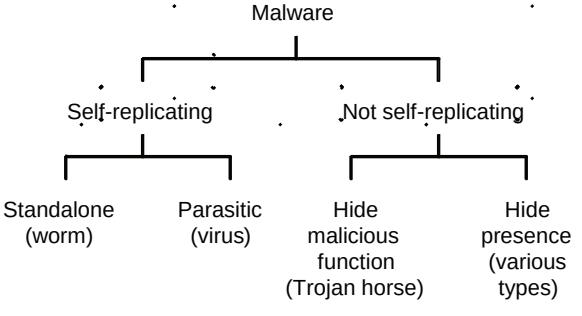
Most people are aware that malicious software (malware) is an ongoing widespread problem with Internet-connected PCs. Statistics about the prevalence of malware, as well as personal anecdotes from affected PC users, are easy to find. PC malware can be traced back to at least the Brain virus in 1986 and the Robert Morris Jr. worm in 1988. Many variants of malware have evolved over 20 years. The October 2006 WildList (www.wildlist.org) contained 780 viruses and worms found to be spreading "in the wild" (on real users' PCs), but this list is known to comprise a small subset of the total number of existing viruses. The prevalence of malware was evident in a 2006 CSI/FBI survey where 65% of the organizations reported being hit by malware, the single most common type of attack.

A taxonomy to introduce definitions of malware is shown in Figure 1, but classification is sometimes difficult because a piece of malware often combines multiple characteristics. Viruses and worms are characterized by the capability to self-replicate,

but they differ in their methods (Nazario, 2004; Szor, 2005). A virus is a piece of software code (set of instructions but not a complete program) attached to a normal program or file. The virus depends on the execution of the host program. At some point in the execution, the virus code hijacks control of the program execution to make copies of itself and attach these copies to more programs or files. In contrast, a worm is a standalone automated program that seeks vulnerable computers through a network and copies itself to compromised victims.

Non-replicating malware typically hide their presence on a computer or at least hide their malicious function. Malware that hides a malicious function but not necessarily its presence is called a Trojan horse (Skoudis, 2004). Typically, Trojan horses pose as a legitimate program (such as a game or device driver) and generally rely on social engineering (deception) because they are not able to self-replicate. Trojan horses are used for various purposes, often theft of confidential data, destruction, backdoor for remote access, or installation of other malware. Besides Trojan horses, many types of non-replicating malware hide their presence in order to carry out a malicious function on a victim host without detection and removal by the user. Common examples include bots and spyware. Bots are covertly installed software that secretly listen for remote commands, usually sent through Internet relay chat (IRC) channels, and execute them on compromised computers. A group of compromised computers under remote control of a single "bot herder" constitute a bot net. Bot nets are often used for spam, data theft, and distributed denial of service attacks. Spyware collects personal user information from a victim computer and transmits the data across the network, often for advertising purposes but possibly for data theft. Spyware is often bundled with shareware or installed covertly through social engineering.

Figure 1. A taxonomy of malicious software



Since 2004, malware has been observed to spread among smartphones and other mobile devices through wireless networks. According to F-Secure, the number of malware known to target smartphones is approximately 100 (Hypponen, 2006). However, some believe that malware will inevitably grow into a serious problem (Dagon, Martin, & Starner, 2004). There have already been complex, blended malware threats on mobile devices. Within a few years, mobile viruses have grown in sophistication in a way reminiscent of 20 years of PC malware evolution. Unfortunately, mobile devices were not designed for security, and they have limited defenses against continually evolving attacks.

If the current trend continues, malware spreading through wireless networks could consume valuable radio resources and substantially degrade the experience of wireless subscribers. In the worst case, malware could become as commonplace in wireless networks as in the Internet with all its attendant risks of data loss, identity theft, and worse. The wireless market is growing quickly, but negative experiences with malware on mobile devices could discourage subscribers and inhibit market growth. The concern is serious because wireless services are currently bound to accounting and charging mechanisms; usage of wireless services, whether for legitimate purposes or malware, will result in subscriber charges. Thus, a victimized subscriber will not only suffer the experience of malware but may also get billed extra service charges. This usage-based charging arrangement contrasts with PCs which typically have flat charges for Internet communications.

This chapter examines historical examples of malware and the current environment for mobile devices. Potential infection vectors are explored. Finally, existing defenses are identified and described.

BACKGROUND

Mobile devices are attractive targets for several reasons (Hypponen, 2006). First, mobile devices have clearly progressed far in terms of hardware and communications. PDAs have grown from simple organizers to miniature computers with their own operating systems (such as Palm or Windows Pocket PC/Windows Mobile) that can download and install a variety of applications. Smartphones combine the communications capabilities of cell phones with PDA functions. According to Gartner, almost 1 billion cell phones will be sold in 2006. Currently, smartphones are a small fraction of the overall cell phone market. According to the *Computer Industry Almanac*, 69 million smartphones will be sold in 2006. However, their shipments are growing rapidly, and IDC predicts smartphones will become 15% of all mobile phones by 2009. Approximately 70% of all smartphones run the Symbian operating system, made by various manufacturers, according to Canalys. Symbian is jointly owned by Sony Ericsson, Nokia, Panasonic, Samsung, and Siemens AG. Symbian is prevalent in Europe and Southeast Asia but less common in North America, Japan, and South Korea. The Japanese and Korean markets have been dominated by Linux-based phones. The North American market has a diversity of cellular platforms.

Nearly all of the malware for smartphones has targeted the Symbian operating system. Descended from Psion Software's EPOC, it is structured similar to desktop operating systems. Traditional cell phones have proprietary embedded operating systems which generally accept only Java applications. In contrast, Symbian application programming interfaces (APIs) are publicly documented so that anyone can develop applications. Applications packaged in SIS file format can be installed at any time, which makes Symbian devices more attractive to both consumers and malware writers.

Mobile devices are attractive targets because they are well connected, often incorporating various means of wireless communications. They are typically capable of Internet access for Web browsing, e-mail, instant messaging, and applications similar to those on PCs. They may also communicate by cellular, IEEE 802.11 wireless LAN, short range Bluetooth, and short/multimedia messaging service (SMS/MMS).

Another reason for their appeal to malware writers is the size of the target population. There were more than 900 million PCs in use worldwide in 2005 and will climb past 1 billion PCs in 2007, according to the *Computer Industry Almanac*. In comparison, there were around 2 billion cellular subscribers in 2005. Such a large target population is attractive for malware writers who want to maximize their impact.

Malware is relatively unknown for mobile devices today. At this time, only a small number of families of malware have been seen for wireless devices, and malware is not a prominent threat in wireless networks. Because of the low threat risk, mobile devices have minimal security defenses. Another reason is the limited processing capacity of mobile devices. Whereas desktop PCs have fast processors and plug into virtually unlimited power, mobile devices have less computing power and limited battery power. Protection such as antivirus software and host-based intrusion detection would incur a relatively high cost in processing and energy consumption. In addition, mobile devices were never designed for security. For example, they lack an encrypting file system, Kerberos authentication, and so on. In short, they are missing all the components required to secure a modern, network-connected computing device.

There is a risk that mobile users may have a false sense of security. Physically, mobile devices feel more personal because they are carried everywhere. Users have complete physical control of them, and hence they feel less accessible to intruders. This sense of security may lead users to trust the devices with more personal data, increasing the risk of loss and appeal to attackers. Also, the sense of security may lead users to neglect security precautions such as changing default security configurations.

Although mobile devices might be appealing targets, there are certain drawbacks to malware for mobile devices. First, mobile devices usually have intermittent connectivity to the network or other devices, in order to save power. This fact limits the ability of malware to spread quickly. Second, if mal-

ware is intended to spread by Bluetooth, Bluetooth connections are short range. Moreover, Bluetooth devices can be turned off or put into hidden mode. Third, there is a diversity of mobile device platforms, in contrast to PCs that are dominated by Windows. Some have argued that the Windows monoculture in PCs has made PCs more vulnerable to malware. To reach a majority of mobile devices, malware writers must create separate pieces of malware code for different platforms (Leavitt, 2005).

EVOLUTION OF MALWARE

Malware has already appeared on mobile devices over the past few years (Peikari & Fogie, 2003). While the number is still small compared to the malware families known for PCs, an examination of prominent examples shows that malware is evolving steadily. The intention here is not to exhaustively list all examples of known malware but to highlight how malware has been developing.

Palm Pilots and Windows Pocket PCs were common before smartphones, and malware appeared first for the Palm operating system. Liberty Crack was a Trojan horse related to Liberty, a program emulating the Nintendo Game Boy on the Palm, reported in August 2000 (Foley & Dumigan, 2001). As a Trojan, it did not spread by self-replication but depended on being installed from a PC that had the "liberty_1_1_crack.prc" file. Once installed on a Palm, it appears on the display as an application, Crack. When executed, it deletes all applications from the Palm (www.f-secure.com/v-descs/lib_palm.shtml).

Discovered in September 2000, Phage was the first virus to target Palm PDAs (Peikari & Fogie, 2003). When executed, the virus infects all third-party applications by overwriting them (http://www.f-secure.com/v-descs/phage.shtml). When a program's icon is selected, the display turns gray and the selected program exits. The virus can spread directly to other Palms by infrared beaming or indirectly through PC synchronization.

Another Trojan horse discovered around the same time, Vapor is installed on a Palm as the application "vapor.prc" (www.f-secure.com/v-descs/vapor.shtml). When executed, it changes the file attributes of other applications, making them invisible (but not actually deleting them). It does not self-replicate.

In July 2004, Duts was a proof-of-concept virus, the first to target Windows Pocket PCs. It asks the user for permission to install. If installed, it attempts to infect all EXE files larger than 4096 bytes in the current directory.

Later in 2004, Brador was a backdoor for Pocket PCs (www.f-secure.com/v-descs/brador.shtml). It installs the file "svchost.exe" in the Startup directory so that it will automatically start during the device bootup. Then it will read the local host IP address and e-mail that to the author. After e-mailing its IP address, the backdoor opens a TCP port and starts listening for commands. The backdoor is capable of uploading and downloading files, executing arbitrary commands, and displaying messages to the PDA user.

The Cabir worm discovered in June 2004 was a milestone marking the trend away from PDAs and towards smartphones running the Symbian operating system. Cabir was a proof-of-concept worm, the first for Symbian, written by a member of a virus writing group 29A (www.f-secure.com/v-descs/cabir.shtml). The worm is carried in a file "caribe.sis" (Caribe is Spanish for the Caribbean). The SIS file contains autostart settings that will automatically execute the worm after the SIS file is installed. When the Cabir worm is activated, it will start looking for other (discoverable) Bluetooth devices within range. Upon finding another device, it will try to send the caribe.sis file. Reception and installation of the file requires user approval after a notification message is displayed. It does not cause any damage.

Cabir was not only one of the first malware for Symbian, but it was also one of the first to use Bluetooth (Gostev, 2006). Malware is more commonly spread by e-mail. The choice of Bluetooth meant that Cabir would spread slowly in the wild. An infected smartphone would have to discover another smartphone within Bluetooth range and the target's user would have to willingly accept the transmission of the worm file while the devices are within range of each other.

In August 2004, the first Trojan horse for smartphones was discovered. It appeared to be a cracked version of a Symbian game Mosquitos. The Trojan made infected phones send SMS text messages to phone numbers resulting in charges to the phones' owners.

In November 2004, the Trojan horse—Skuller—was found to infect Symbian Series 60 smartphones (www.f-secure.com/v-descs/skulls.shtml). The Trojan is a file named "Extended theme.SIS," a theme manager for Nokia 7610 smartphones. If executed, it disables all applications on the phone and replaces their icons with a skull and crossbones. The phone can be used to make calls and answer calls. However, all system applications such as SMS, MMS, Web browsing, and camera do not work.

In December 2004, Skuller and Cabir were merged to form Metal Gear, a Trojan horse that masquerades as the game of the same name. Metal Gear uses Skulls to deactivate a device's antivirus. This was the first malware to attack antivirus on Symbian smartphones. The malware also drops a file "SEXXXY.SIS," an installer that adds code to disable the handset menu button. It then uses Cabir to send itself to other devices.

Locknut was a Trojan horse discovered in February 2005 that pretended to be a patch for Symbian Series 60 phones. When installed, it drops a program that will crash a critical system service component, preventing any application from launching.

In March 2005, ComWar or CommWarrior was the first worm to spread by MMS among Symbian Series 60 smartphones. Like Cabir, it was also capable of spreading by Bluetooth. Infected phones will search for discoverable Bluetooth devices within range; if found, the infected phone will try to send the worm in a randomly named SIS file. But Bluetooth is limited to devices within 10 meters or so. MMS messages can be sent to anywhere in the world. The worm tries to spread by MMS messaging to other phone owners found in the victim's address book. MMS has the unfortunate side effect of incurring charges for the phone owner.

Drever was a Trojan horse that attacked antivirus software on Symbian smartphones. It drops non-functional copies of the bootloaders used by Simworks Antivirus and Kaspersky Symbian Antivirus, preventing these programs from loading automatically during the phone bootup.

In April 2005, the Mabir worm was similar to Cabir in its ability to spread by Bluetooth. It had the additional capability to spread by MMS messaging. It listens for any arriving MMS or SMS message and will respond with a copy of itself in a file named "info.sis."

Found in September 2005, the Cardtrap Trojan horse targeted Symbian 60 smartphones and was one of the first examples of smartphone malware capable of infecting a PC (www.f-secure.com/v-descs/cardtrap_a.shtml). When it is installed on the smartphone, it disables several applications by overwriting their main executable files. More interestingly, it also installs two Windows worms, Padobot.Z and Rays, to the phone's memory card. An autorun file is copied with the Padobot.Z worm, so that if the memory card is inserted into a PC, the autorun file will attempt to execute the Padobot worm. The Rays worm is a file named "system.exe" which has the same icon as the system folder in the memory card. The evident intention was to trick a user reading the contents of the card on a PC into executing the Rays worm.

Crossover was a proof-of-concept Trojan horse found in February 2006. It was reportedly the first malware capable of spreading from a PC to a Windows Mobile Pocket PC by means of ActiveSync. On the PC, the Trojan checks the version of the host operating system. If it is not Windows CE or Windows Mobile, the virus makes a copy of itself on the PC and adds a registry entry to execute the virus during PC rebooting. A new virus copy is made with a random file name at each reboot. When executed, the Trojan waits for an ActiveSync connection, when it copies itself to the handheld, documents on the handheld will be deleted.

In August 2006, the Mobler worm for Windows PCs was discovered (www.f-secure.com/v-descs/mobler.shtml). It is not a real threat but is suggestive of how future malware might evolve. When a PC is infected, the worm copies itself to different folders on local hard drives and writable media (such as a memory card). Among its various actions, the

worm creates a SIS archiver program "makesis.exe" and a copy of itself named "system.exe" in the Windows system folder. It also creates a Symbian installation package named "Black_Symbian.SIS." It is believed to be capable of spreading from a PC to smartphone, another example of cross-platform malware.

At the current time, it is unknown whether Crossover and Mobler signal the start of a new trend towards cross-platform malware that spread equally well among PCs and mobile devices. The combined potential target population would be nearly 3 billion. The trend is not obvious yet but Crossover and Mobler suggest that cross-platform malware could become possible in the near future.

INFECTION VECTORS

Infection vectors for PC malware have changed over the years as PC technology evolved. Viruses initially spread by floppy disks. After floppy disks disappeared and Internet connectivity became ubiquitous, worms spread by mass e-mailing. Similarly, infection vectors used by malware for mobile devices have changed over the past few years.

Synchronization: Palm and Windows PDAs were popular before smartphones. PDAs install software by synchronization with PCs (Foley & Dumigan, 2001). For example, Palm applications are packaged as Palm resource (PRC) files installed from PCs. As seen earlier, Palm malware usually relied on social engineering to get installed. This is a slow infection vector for malware to spread between PDAs because it requires synchronization with a PC and then contact with another PC that synchronizes with another PDA. Much faster infection vectors became possible when PDAs and then smartphones started to feature communications directly between mobile devices without having to go through PCs.

E-mail and Web: Internet access from mobile devices allows users away from their desktops to use the most common Internet applications, e-mail and the World Wide Web. Most mobile devices can send and receive e-mail with attachments. In addition, many can access the Web through a microbrowser designed to render Web content on the small displays of mobile devices. Current microbrowsers are similar in features to regular Web browsers, capable of HTML, WML, CSS, Ajax, and plug-ins. Although e-mail and the Web are common vectors for PC malware, they have not been used as vectors to infect mobile devices thus far.

SMS/MMS messaging: Commonly called text messaging, SMS is available on most mobile phones and Pocket PCs. It is most popular in Europe, Asia (excluding Japan), Australia, and New Zealand, but has not been as popular in the U.S. as other types of messaging. Text messaging is often used to interact with automated systems, for example to order products or services or participate in contests. Short messages are limited to 140 bytes of data, but longer content can be segmented and sent in multiple messages. The receiving phone is responsible for reassembling the complete message. Short messages can also be used to send binary content such as ringtones or logos. While SMS is largely limited to text, MMS is a more advanced messaging service allowing transmission of multimedia objects—video, images, audio, and rich text. The ComWar worm was the first to spread by MMS (among Symbian Series 60 smartphones). MMS has the potential to spread quickly. ComWar increased its chances by targeting other phone owners found in the victim's address book. By appearing to come from an acquaintance, an incoming message is more likely to be accepted by a recipient. MMS will likely continue to be an infection vector in the future.

Bluetooth: Bluetooth is a short-range radio communication protocol that allows Bluetooth-enabled devices (which could be mobile or stationary) within 10-100 meters to discover and talk with each other. Up to eight devices can communicate with each other in a piconet, where one device works in the role of "master" and the others in the role of "slaves." The master takes turns to communicate with each slave by round robin. The roles of master and slaves can be changed at any time.

Each Bluetooth device has a unique and permanent 48-bit address as well as a user-chosen Bluetooth name. Any device can search for other

nearby devices, and devices configured to respond will give their name, class, list of services, and technical details (e.g., manufacturer, device features). If a device inquires directly at a device's address, it will always respond with the requested information.

In May 2006, F-Secure and Secure Networks conducted a survey of discoverable Bluetooth devices in a variety of places in Italy. They found on average 29 to 154 Bluetooth devices per hour in discoverable mode in the different places. In discoverable mode, the devices are potentially open to attacks. About 24% were found to have visible OBEX push service. This service is normally used for transfer of electronic business cards or similar information, but is known to be vulnerable to a BlueSnarf attack. This attack allows connections to a cellular phone and access to the phone book and agenda without authorization. Another vulnerability is BlueBug, discovered in March 2004, allowing access to the ASCII Terminal (AT) commands of a cell phone. These set of commands are common for configuration and control of telecommunications devices, and give high-level control over call control and SMS messaging. In effect, these can allow an attacker to use the phone services without the victim's knowledge. This includes incoming and outgoing phone calls and SMS messages.

The Cabir worm was the first to use Bluetooth as a vector. Bluetooth is expected to be a slow infection vector. An infected smartphone would have to discover another smartphone within a 10-meter range, and the target's user would have to willingly accept the transmission of the worm file while the devices are within range of each other. Moreover, although phones are usually shipped with Bluetooth in discoverable mode, it is simple to change devices to invisible mode. This simple precaution would make it much more difficult for malware.

MALWARE DEFENSES

Practical security depends on multiple layers of protection instead of a single (hopefully perfect) defense (Skoudis, 2004). Fortunately, various defenses against malware have been developed from decades of experience with PC malware. A taxonomy of malware defenses is shown in Figure 2. Defenses can be first categorized as preventive or reactive (defensive). Preventive techniques help avoid malware infections through identification and remediation of vulnerabilities, strengthening security policies, patching operating systems and applications, updating antivirus signatures, and even educating users about best practices (in this case, for example, turning off Bluetooth except when needed, rejecting installation of unknown software, and blocking SMS/MMS messages from untrusted parties). At this time, simple preventive techniques are likely to be very effective because there are relatively few threats that really spread in the wild. In particular, education to raise user awareness would be effective against social engineering, one of the main infection vectors used by malware for mobile devices so far.

Host-Based Defenses

Even with the best practices to avoid infections, reactive defenses are still needed to protect mobile devices from actual malware threats. Reactive defenses can operate in hosts (mobile devices) or within the network. Host-based defenses make sense because protection will be close to the targets. However, host-based processes (e.g., antivirus programs) consume processing and power resources that are more critical on mobile devices than desktop PCs. Also, the approach is difficult to scale to large populations if software must be installed, managed, and maintained on every mobile device. Network-based defenses are more scalable in the sense that one router or firewall may protect a group of hosts. Another reason for network-based defenses is the possibility that the network might be able to block malware before it actually reaches a targeted device, which is not possible with host-based defenses. Host-based defenses take effect after contact with the host. In practice, host-based and network-based defenses are both used in combination to realize their complementary benefits.

The most obvious host-based defense is antivirus software (Szor, 2005). Antivirus does automatic analysis of files, communicated messages, and system activities. All commercial antivirus programs depend mainly on malware signatures which are sets of unique characteristics associated with each known piece of malware. The main advantage of signature-based detection is its accuracy in malware identification. If a signature is matched, then the malware is identified exactly and perhaps sufficiently for disinfection. Unfortunately, signature-based detection has two drawbacks. First, antivirus signatures must be regularly updated. Second, there will always be the possibility that new malware could escape detection if it does not have a matching signature. For that case, antivirus programs often include heuristic anomaly detection which detects unusual behavior or activities. Anomaly detection does not usually identify malware exactly, only the suspicion of the presence of malware and the need for further investigation. For that reason, signatures will continue to be the preferred antivirus method for the foreseeable future.

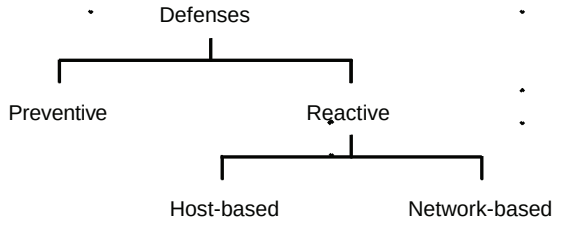
Several antivirus products are available for smartphones and PDAs. In October 2005, Nokia and Symantec arranged for Nokia to offer the option of preloading Symbian Series 60 smartphones with Symantec Mobile Security Antivirus. Other commercial antivirus packages can be installed on Symbian or Windows Mobile smartphones and PDAs.

In recognition that nearly all smartphone malware has targeted Symbian devices, a great amount of attention has focused on the vulnerabilities of that operating system. It might be argued that the system has a low level of application security. For example, Symbian allows any system application to be rewritten without requiring user consent. Also, after an application is installed, it has total control over all functions. In short, applications are totally trusted.

Although Windows CE has not been as popular a target, it has similar vulnerabilities. There are no restrictions on applications; once launched, an application has full access to any system function including sending/receiving files, phone functions, multimedia functions, and so forth. Moreover, Windows CE is an open platform and application development is relatively easy.

Symbian OS version 9 added the feature of code signing. Currently all software must be manually installed. The installation process warns the user if an application has not been signed. Digital signing makes software traceable to the developer and verifies that an application has not been changed since it left the developer. Developers can apply to have their software signed via the Symbian Signed program (www.symbiansigned.com). Developers also have the option of self-signing their programs. Any signed application will install on a Symbian OS phone without showing a security warning. An unsigned application can be installed with user consent, but the operating system will prevent it from doing potentially damaging things by denying access to key system functions and data storage of other applications.

Figure 2. A taxonomy of malware defenses



Network-Based Defenses

Network-based defenses depend on network operators monitoring, analyzing, and filtering the traffic going through their networks. Security equipment include firewalls, intrusion detection systems, routers with access control lists (ACLs), and antivirus running in e-mail servers and SMS/MMS messaging service centers. Traffic analysis is typically done by signature-based detection, similar in concept to signature-based antivirus, augmented with heuristic anomaly based detection.

Traffic filtering is done by configuring firewall and ACL policies.

An example is Sprint's Mobile Security service announced in September 2006. This is a set of managed security services for mobile devices from handhelds to laptops. The service includes protection against malware attacks. The service can scan mobile devices and remove detected malware automatically without requiring user action.

In the longer term, mobile device security may be driven by one or more vendor groups working to improve the security of wireless systems. For instance, the Trusted Computing Group (TCG) (www.trustedcomputinggroup.org) is an organization of more than 100 component manufacturers, software developers, networking companies, and service providers formed in 2003. One subgroup is working on a set of specifications for mobile phone security (TCG, 2006a). Their approach is to develop a Mobile Trusted Module (MTM) specification for hardware to support features similar to those of the Trusted Platform Module (TPM) chip used in computers but with additional functions specifically for mobile devices. The TPM is a tamper-proof chip embedded at the PC board level, serving as the "root of trust" for all system activities. The MTM specification will integrate security into smartphones' core operations instead of adding as applications.

Another subgroup is working on specifications for Trusted Network Connect (TCG, 2006b). All hosts including mobile devices run TNC client software, which collects information about that host's current state of security such as antivirus signature updates, software patching level, results of last security scan, firewall configuration, and any other active security processes. The security state information is sent to a TNC server to check against policies set by network administrators. The server makes a decision to grant or deny access to the network. This ensures that hosts are properly configured and protected before connecting to the network. It is important to verify that hosts are not vulnerable to threats from the network and do not pose a threat to other hosts. Otherwise, they will be effectively quarantined from the network until their security state is remedied. Remedies can include software patching, updating antivirus, or any other changes to bring the host into compliance with security policies.

FUTURE TRENDS

It is easy to see that mobile phones are increasingly attractive as malware targets. The number of smartphones and their percentage of overall mobile devices is growing quickly. Smartphones will continue to increase in functionalities and complexity. Symbian has been the primary target, a trend that will continue as long as it is the predominant smartphone platform. If another platform arises, that will attract the attention of malware writers who want to make the biggest impact.

The review of malware evolution suggests a worrisome trend. Since the first worm, Cabir, only three years ago, malware has advanced steadily to more infection vectors, first Bluetooth and then MMS. Recently malware has shown signs of becoming cross-platform, moving easily between mobile devices and PCs.

Fortunately, mobile security has already drawn the activities of the TCG and other industry organizations. Unlike the malware situation with PCs, the telecommunications industry has decades of experience to apply to wireless networks, and there is time to fortify defenses before malware multiplies into a global epidemic.

CONCLUSION

Malware is a low risk threat for mobile devices today, but the situation is unlikely to stay that way for long. It is evident from this review that mobile phones are starting to attract the attention of malware writers, a trend that will only get worse. At this point, most defenses are common sense practices. The wireless industry realizes that the stakes are high. Two billion mobile users currently enjoy a malware-free experience, but negative experiences with new malware could have a disastrous effect. Fortunately, a range of host-based and network-based defenses have been developed

from experience with PC malware. Activities are underway in the industry to improve protection of mobile devices before the malware problem becomes catastrophic.

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KEY TERMS

Antivirus Software: Antivirus software is designed to detect and remove computer viruses and worms and prevent their reoccurrence.

Exploit Software: Exploit software is written to attack and take advantage of a specific vulnerability.

Malware Software: Malware software is any type of software with malicious function, including for example, viruses, worms, Trojan horses, and spyware.

Smartphone: Smartphones are devices with the combined functions of cell phones and PDAs, typically running an operating system such as Symbian OS.

Social Engineering: Social engineering is an attack method taking advantage of human nature.

Trojan Horse: A Trojan horse is any software program containing a covert malicious function.

Virus: A virus is a piece of a software program that attaches to a normal program or file and depends on execution of the host program to self-replicate and infect more programs or files.

Vulnerability: Vulnerability is a security flaw in operating systems or applications that could be exploited to attack the host.

Worm: A worm is a stand-alone malicious program that is capable of automated self-replication.

Chapter II
Secure Service Discovery

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ABSTRACT

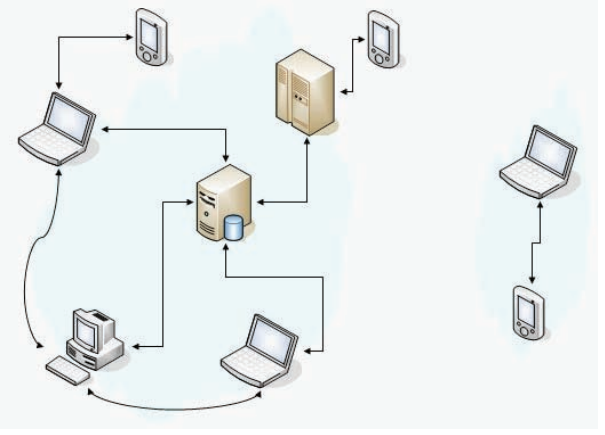
In broadband wireless networks, mobile devices will be equipped to directly share resources using service discovery mechanisms without relying upon centralized servers or infrastructure support. The network environment will frequently be ad hoc or will cross administrative boundaries. There are many challenges to enabling secure and private service discovery in these environments including the dynamic population of participants, the lack of a universal trust mechanism, and the limited capabilities of the devices. To ensure secure service discovery while addressing privacy issues, trust-based models are inevitable. We survey secure service discovery in the broadband wireless environment. We include case studies of two protocols that include a trust mechanism, and we summarize future research directions.

INTRODUCTION

Service orientation is widely used in client-server computing and is growing in importance for mobile wireless devices. In this way, a device's software and hardware components can be packaged as services for use by other devices. Many consumer electronics (CE) devices are specialized for specific uses. Due to form factor and cost considerations, devices vary in capability. With sufficiently high bandwidth network interfaces on these devices, such as 802.11, WiMax, and ultra-wideband (UWB), it is practical for sets of networked devices to share functionality. Service discovery and advertisement (SDA) is fundamental to service interoperability in pervasive computing applications.

Many service discovery protocols have been developed, including several for specific wireless networks. However, few of these protocols have been designed with security mechanisms and the majority use centralized enforcement and validation. Due to the emergence of mobile and large-scale peer-to-peer applications, there is growing

Figure 1. Different types of networks in a pervasive computing environment. (a) Ad hoc network in a pervasive environment with powerful device support. (b) Ad hoc network in a pervasive environment without powerful device support.



(a) *(b)*

interest in security mechanisms that do not require centralized enforcement and validation.

We present the current state of secure service discovery. Leading designs for secure service discovery are surveyed including industry standards and research systems. The types of security issues we are concerned with include: protecting the privacy of service advertisements and descriptions; authentication of service advertisements; secure distribution and updating of keys for service invocation; providing trust in service composition; and limiting vulnerability to attacks effecting the service discovery mechanism.

Pervasive computing environment focuses (Weiser, 1991, 1993) has evolved over the past few years with the availability of portable low-cost devices (such as PDAs, cell phones, smart phones, laptops, and sensors) and the emergence of short-range and low-power wireless communication networks. Pervasive computing environments focus on integrating computing and communications with the surrounding physical environment to make computing and communication transparent to the users in everyday contexts. In a broad sense, pervasive computing combines mobile computing, wireless networks, embedded computing, and context-aware sensor networks (Robinson, Vogt, & Wagealla, 2005).

The different kinds of networks in pervasive computing environments impact the design of secure service discovery mechanisms. On one end, there are smart spaces, or intelligent environments that provide devices with a variety of support for user awareness and context management, while at the other end there are networks that provide open network connectivity.

Figure 1 depicts two ad hoc networks in a pervasive computing environment. In Figure 1a, the devices communicate among themselves with the support of fixed, more powerful devices. These devices act as servers or proxies for the mobile devices. In Figure 1b, an ad hoc network is formed by mobile devices. There is no fixed infrastructure support. The devices communicate with each other directly or via another mobile device, and are responsible for performing computations by themselves.

In service discovery (Kindberg & Fox, 2002; Lee & Helal, 2002), a device searches for another device capable of offering a specific service or resource. An important trend is the adoption of a service-oriented architecture for resource discovery, not just for server systems accessed by

mobile devices, but also for sharing of resources between devices. There are four elements found in the service-oriented approach: (1) service description, which provides an interchangeable way for devices to describe the service and its use; (2) service registration or advertisement on behalf of the service provider; (3) service discovery by devices seeking a service; and (4) service invocation, which is a protocol by which a service requester and service provider coordinate to deliver a service. Propagation of service advertisements can be using pull (query), push (announcement), or a combination of pull and push. In addition, the ability to dynamically discover and combine component services to form new services is referred to as service composition.

Broadband wireless technologies such as WiMax, UWB, and 802.11n are bringing broadband connectivity to mobile CE devices. These devices will be able to switch between different network access technologies. This has the following consequences for service discovery in pervasive computing:

- Due to broadband connectivity, devices will be able to participate in media-rich and sophisticated resource sharing.
- Wide-area service discovery and location-based discovery will grow in importance due to the combination of increased connectivity and wide-area roaming.
- The ability to act as multi-homed devices means that devices will have increased connectivity but also an increased rate of transitions due to roaming between different networks.
- Devices will be able to simultaneously participate in a personal area network (PAN), home networks, and wireless area networks (WANs) with different security and trust properties. In PANs and home networks, mediation of service discovery between networks is needed, in which devices such as gateways proxy or intermediate service discovery between network domains.
- Device-to-device interaction will grow in importance to users for applications such as content sharing, communication, and gaming.

Due to these trends, richer models of discovery are being considered such as federated discovery, meta discovery, and semantic discovery (Buford, Brown, & Kolberg, 2006; Buford, Celebi, & Frankl, 2006).

Consequently, it is important for wireless devices to securely participate in service discovery with other devices that are outside the immediate administrative security domain. Further, these devices interact with other devices in an ad hoc manner, and lack of fixed infrastructure support leads to the dependency on other devices for resources. The nature of devices, communication patterns, and dependency on other devices in turn causes security vulnerabilities. Due to the ad hoc connectivity and dynamic nature of the population of devices, access to specific devices may be intermittent and short-lived. Moreover, multiple devices may concurrently request one specific resource. These aspects demand a scalable, efficient, and responsive service discovery model.

Thus far, we have discussed the general view of and motivation for service discovery for mobile devices. The rest of the chapter is organized as follows: The next section summarizes the security goals for service discovery and presents a model for service discovery in pervasive computing. The third section surveys present unsecured service discovery models. The fourth section surveys existing secure service discovery models, organized into three different categories. Two case studies of service discovery protocols that incorporate trust-based mechanisms are described in the *Examples Using Trust Models* section. The final sections summarize important research issues and conclusions.

Security Goals in Service Discovery, Invocation, and Composition

The significance of security during service discovery is well established (Matsumiya et al., 2004; Stajano, 2002; Stajano & Anderson, 2002). Privacy, security, and trust issues in service discovery in the

pervasive computing area are of utmost importance (Robinson et al., 2005). Thus, the service discovery process demands models that ensure the privacy and security of the user. In particular, this privacy and security should encompass:

- **Authentication:** Does the user and device actually have the indicated identity?
- **Authorization:** Does the user have access rights for issuing service advertisements, requesting services, and invoking services?
- **Trust:** Are the participating user and device trusted? Are the service and its components trusted?
- **Privacy:** Is only the approved information shared between the given users/devices during service discovery, advertisement and invocation (SDAI) operations? Is disclosure to unauthorized users prevented?
- **Vulnerability to attack and misuse:** Are the SDAI operations protected from attacks such as denial-of-service, spoofing, replay, and man-in-the-middle? Are the SDAI operations protected from misuse in enabling such attacks on other network components?

An important question is what security, privacy, and trust mechanisms are provided by the wireless network. IEEE 802.11i, also known as WiFi Protected Access 2 (WPA2), replaced Wired Equivalent Privacy (WEP) with stronger encryption and a new authentication mechanism incorporating an authentication server such as remote authentication dial in user service (RADIUS). This mechanism while suitable for enterprise deployment has had limited use in home networks because of complex administration and in public hot spots due to difficulty administering shared keys. Thus, in the best case, a set of devices are authenticated in a single administrative domain, and the authentication server can be used to support authorization policies including policies related to service discovery and use. Network packets between authenticated users are encrypted, providing communication privacy from non-authenticated parties. However, these security capabilities cover only a subset of the aforementioned security goals and are limited to single administrative domains. For interactions crossing administrative boundaries, or without infrastructure support, other mechanisms are needed.

Further, traditional security mechanisms do not work well in this environment because the devices are computationally limited and the notion of physical security is not applicable (Kagal, Finin, & Joshi, 2001). Then, considering the choices of totally sacrificing security versus imposing a full-fledged security structure similar to desktops and laptops, the question is whether there is any middle ground. Ensuring varying levels of security for various services is a research challenge. The insufficiency of user/device identity for trust is another concern in designing a discovery model, and techniques for peer trust and risk assessment (Chen, Jensen, Gray, Cahill, & Seigneur, 2003) are important tools to address this.

Desired characteristics of a secure and private service discovery model are summarized next.

- **Adaptive:** The trust value and security level should be adaptable depending on the service itself, the service provider, and the service requester.
- **Trust reliant:** The model should consider trust relationships among devices. Where no prior information is available, reputation, recommendation, or trust negotiation schemes can be used. If these are unsuitable, then risk assessment can be used.
- **Infrastructure independence:** No infrastructure support (e.g., powerful servers, proxies) should be required. Then the model should work independently without any external support, but be able to leverage infrastructure where it exists.
- **Lightweight:** The model should be lightweight in terms of executable file size.
- **Service oriented:** To control service security modularly, service discovery models should be service oriented.
- **Graceful performance degradation:** The model should not put much overhead on the performance of the device, and performance should degrade gracefully for more advanced security features.

- **Energy efficient:** Service discovery models should be energy conserving, for example, avoiding continuous broadcasting or polling.

A classification and detailed survey of service discovery models can be found in Zhu, Mutka, and Ni (2002). Service-oriented architectures (SOA) and their security are discussed in Cotroneo, Graziano, and Russo (2004). We classify existing service discovery models into two broad categories. First are service discovery models that do not address security issues (Balazinska, Balakrishnan, & Karger, 2002; Microsoft, 2000; Miller, Nixon, Tai, & Wood, 2001; Nidd, 2001; Winoto, Schwartz, Balakrishnan, & Lilley, 1999). Second, there are models that consider a full-fledged security mechanism with the help of infrastructure support (Czerwinski, Zhao, Hodes, Joseph, & Katz, 1999; Zhu, Mutka, & Ni, 2003, 2004). The next two sections discuss examples of these cases, and Table 1 compares the key features of the surveyed systems.

SERVICE DISCOVERY MODELS WITHOUT INHERENT SECURITY

We describe several designs that do not address security requirements. Nevertheless these models are important either because the systems are widely used, are representative approaches, or could be secured by additional mechanisms in a secure network. The designs we discuss are Bluetooth, DEAPSpace, and Intentional Naming System (INS).

Bluetooth (Bluetooth Special Interest Group [SIG], 2001a, 2001b) is a pull protocol. Device information, services, and the characteristics of the services are queried and connections between two or more Bluetooth devices are established. This facilitates user selection, scope-awareness, and both unicast and broadcast communication. A Bluetooth device returns all matched resource information.

Nidd (2001) developed the DEAPSpace service discovery method for ad hoc and mobile device applications. Each node broadcasts its advertisement of local services. After receiving a broadcast, each node updates its service list with information about the other nodes' services. This service information is included in that node's subsequent broadcast. Each node is a broadcaster and DEAPSpace uses contention timers at each node so that a node will randomly delay its broadcast after another broadcast is received. DEAPSpace can reduce service discovery time at the cost of increased bandwidth and power consumption.

INS (Winoto et al., 1999) supports both pull and push delivery of service advertisements. It also supports unicast, anycast, and broadcast methods. It offers the best-match resource information and also provides facilities for limited support of context information. In INS each device requests a central name resolver for the type of services it requires, and the resolver replies with the best matched device address.

Secure Service Discovery Models

Most contemporary service discovery models fall into this category. There are some models that include full-fledged security mechanisms, while others rely on simple algorithms for limited security. This category can be subdivided into infrastructure based, infrastructureless, hardware based, and smart-space-oriented security mechanisms. In the following subsections we discuss each of these categories.

Infrastructure-Based Security

UPnP is a specification for connecting multiple devices on a home network so that these devices can invoke services of each other. UPnP defines a set of protocols and a service description format. In addition, UPnP standardizes various service interfaces. UPnP relies on administratively scoped multicast IP address for service discovery, service advertisement, and event delivery. Each UPnP device broadcasts its advertisements when it first connects to the network. Thereafter, a UPnP device broadcasts advertisements in response to queries from other devices. These queries may be for all services on the network or a specific service on

Table 1. Comparison of secure service discovery models (SSDS): SSDS (Czerwinski et al., 1999), Ninja (Goldberg, Gribble, Wagner, & Brewer, 1999; Gribble et al., 2001), UPnP (Miller et al., 2001), SPDP (Almenarez & Campo, 2003), Progressive Exposure (Zhu et al., 2004; Zhu, Mutka, & Ni, 2006), Splendor (Kagal, Korolev, Chen, Joshi, & Finin, 2001), Jini (Sun Microsystems, 2001), CSAS (Minami & Kotz, 2005), CSM (Brezillon & Mostefaoui, 2004), AVCM (Shankar & Arbaugh, 2002), CSRA (Tripathi, Ahmed, Kulkarni, Kumar, & Kashiramka, 2004), TRAC (Basu & Callaghan, 2005), SME (Kopp, Lucke, & Tavangarian, 2005), HCA (Pearson, 2005), SSRD (Sharmin, Ahmed, & Ahamed, 2006a), SSRD+ (Sharmin, Ahmed, & Ahamed, 2006b), Centaurus2 (Undercoffer, Perich, Cedilnik, Kagal, & Joshi, 2003), SLP (Barbeau, 1999; Guttman, Perkins, Veizades, & Day, 1999), Sleeper (Buford, Celebi, et al., 2006)

Model	Adaptive	Infrastructure Support Needed	Lightweight	Service-Oriented	Trust Aware	Privacy Aware	Context Aware	Smart Space Needed
SSDS	No	Yes	No	No	N/A	N/A	N/A	No
Ninja	No	Yes	No	No	N/A	N/A	N/A	No
UPnP	No	N/A	No	No	No	Yes	No	Limited
SPDP	No	No	Yes	No	Yes	N/A	No	No
Progressive Exposure	No	Yes	No	No	No	Yes	Limited	No
Splendor	No	Yes	No	No	Yes	Yes	N/A	No
Jini	No	N/A	No	No	N/A	Yes	N/A	Limited
CSAS	No	No	Yes	No	N/A	N/A	Yes	No
CSM	Yes	No	Yes	No	N/A	N/A	Yes	No
AVCM	Limited	No	Yes	No	Yes	Yes	Yes	No
CSRA	No	Yes	No	No	N/A	N/A	Yes	Yes
TRAC	No	N/A	No	No	Yes	Yes	N/A	Yes
SME	Yes	N/A	N/A	Yes	N/A	Yes	No	N/A
HCA	No	N/A	Yes	No	No	Yes	No	N/A
SSRD	Yes	No	Yes	Yes	Yes	Yes	Limited	No
SSRD+	Yes	No	Yes	Yes	Yes	Limited	Yes	No
Centaurus2	Yes	Yes	No	No	No	N/A	Yes	No
SLP	No	Yes	Yes	Yes	No	No	No	No
Sleeper	Yes	No	Yes	Yes	Yes	Yes	No	No

the network. UPnP Device Security specification defines security mechanisms for simple object access protocol (SOAP)-based service invocation, but does not address simple service discovery protocol (SSDP) security.

As an extension of project Centaurus (Kagal, Korolev, Avancha, et al., 2001; Kagal, Korolev, Chen, et al., 2001), Centaurus2 (Undercoffer et al., 2003) provides a secure mechanism for service discovery and enables users to access services across heterogeneous network domains. The system uses a local certificate authority (CA) and each entity must be pre-registered in the system. The CA issues a certificate to each identified and verified entity. The design of Centaurus2 includes four components, and each component has a separate private key which is stored at the client using PKCS #11:

1. The local CA is responsible for issuing digital certificates and for validating these digital certificates.

2. The communication manager mediates communication between clients and networked services.
3. Group membership(s) is maintained and stored by the capability manager.
4. Each client is registered to a specific service manager that ensures security, access rights, and mediates between user client and service client. Service managers maintain a service registry.

Each domain has a root service manager. Static bridges are configured between service managers in different domains. Then clients in separate domains can access services across domains using the root service manager as the context.

In SSDS (Czerwinski et al., 1999), both service advertisement pull (query) and push (announcement) are supported. Service advertisements are stored in a hierarchy of servers. SSDS provides capability-based access control. All information passed between clients and servers is encrypted. A single copy of the resource information is stored and accessed, which makes the system vulnerable to single point failure. Subsequently, the Ninja project (Goldberg et al., 1999; Gribble et al., 2001) added the concept of secure identification of service through SSDS. In Ninja, the CA issues valid certificates and the capability manager authorizes user access to a particular resource. The service providers can also prescribe the conditions (capabilities) that are needed by a user in order to discover a particular service.

The context-sensitive authorization scheme (CSAS) (Minami & Kotz, 2005) provides authorization without a central server or CA. When a CSAS user wants to access a service from a resource, the associated server issues a logical authentication query and sends it to the host of the resource. Each host has a knowledge domain with which it attempts to prove the authorization query. If it fails, it distributes several portions of the proof to multiple hosts. Through this distribution CSAS reduces the computational overhead on any single node. After collecting the sub-proofs from the other hosts, the host of the resource can declare the result of the query to be true or false, thus indicating grant of access or denial respectively. This approach facilitates confidentiality, integrity, and scalability. To authorize access, CSAS uses previously stored information, which may be difficult to collect for users in an ad hoc network.

Splendor (Zhu et al., 2003) is a secure, private, and location-aware service discovery protocol. Splendor adapts depending on the network environment to use either a client-service model or client-service-directory model. Proxies are used to offload workload for mobile services. Mobile services authenticate with proxies and proxies handle registration. In these situations, proxies are considered to be trusted servers. However, if no trusted server is available in an environment, then there is no agent to handle the registration. Its security model is based on mutual authentication.

Progressive Exposure (Zhu et al., 2004, 2006) is a secure service discovery approach. It addresses privacy issues using a mutual matching technique. Progressive exposure addresses security and fairness by not exposing too much information. In each round of message exchange between communicating parties, it tries to find whether any mismatch occurs. In case of a mismatch, the communication stops. It uses one-time code words and a hash-based message authentication code. It considers the presence of one user and one service provider, but it does not address situations in which many users and many service providers are present. When a service provider leaves the network, the process of provider lookup and the authentication phase is restarted. It provides privacy for service information, requests, domain identity, and user credentials, and is based on the client-service-directory model.

Infrastructure-Less Security

SPDP (Almenarez & Campo, 2003) is a secure service discovery protocol based on the PTM (Almenarez, Marin, Campo, & Garcia, 2004; Almenarez, Marin, Dyaz, & Sanchez, 2006) model. The need for a centralized server is avoided by having each device act as its own CA. For a service request, this model uses broadcast messaging. The requesting device updates its cache after getting a

reply from the devices (if any reply). It then stores the device identities that it believes trustworthy. The devices' user agents continually listen for messages, which in turn means continual energy consumption.

Narendar Sarkar et al. (Shankar & Arbaugh, 2002) propose an attribute vector calculus (AVCM) for modeling trust. Their model describes both identity-based trust and context-based trust and is one of the first models that discusses the importance of trust in a ubiquitous environment. Brezillion and Mostefaoui (2004) present a context-based security model (CSM) and they discuss the need for adaptive security based on the particular situation. Thomas and Sandhu (2004) present the challenges and research issues for secure pervasive computing. They express the need for a dynamic trust model as the pervasive computing environment poses new kinds of security challenges due to its diverse nature. They present a socio-technical view.

Smart Space Dependent Security

A smart space provides devices with complex computational support that supports context-awareness and collaboration. Components of the smart space can offload secure discovery tasks and relate them to other activities in the space. Examples include context-based secure resource access (CSRA) (Tripathi et al., 2004) and trust-based architecture (TRAC) (Basu & Callaghan, 2005).

CSRA (Tripathi et al., 2004) focuses on context-aware discovery of resources and how to access resources in a secure and unobtrusive manner. In a pervasive computing environment the rules and limitations imposed by the user, system, and the collaborative activity scenario have to be combined dynamically at runtime. CSRA uses a namespace related to each user and domain. These namespaces collect resources, services, and activities. The binding protocol defines the association of a user to a specific resource in the space. The binding changes based on the contextual information of the user including the location, activity, and role. A descriptor is associated with each namespace that combines functional attributes collected from resource descriptions in Web services description language (WSDL) and resource description framework (RDF) conditions for security, and policies for the binding protocol. The binding protocol specifies whether the binding of a resource is "shared" or "private," and whether the binding is "permanent" or "context-based."

Basu and Callaghan (2005) present a TRAC for increasing security and user confidence in pervasive computing systems. They use trust and role-based access control for ensuring security and privacy. However their model is aimed at an intelligent environment (IE) only. This policy-based model allows users to define policies for themselves and thus gives users control to define their own security level. This model works in an IE because every user is known beforehand. However, in a truly pervasive environment it is not possible to have prior information about every user and thus, this model is not applicable.

EXAMPLES USING TRUST MODELS

We next describe two service discovery protocols, Sleeper and SSRD, which incorporate trust models for infrastructure-less security.

Sleeper

Sleeper (Buford, Celebi, et al., 2006) is an energy-preserving service discovery protocol which features dynamic proxy selection for advertisement and discovery so that nodes can go to power standby while the proxy advertises on their behalf. The basic node states and transitions for Sleeper are shown in Figure 2. An off-line or disconnected node moves to an online state and broadcasts a *join* message that includes its advertisements and their popularity metrics. The current proxy caches these advertisements. Any proxy-candidate node may also cache these advertisements. An online node may broadcast a *leave* message prior to going off-line; if a leave message is not transmitted, advertisements may be purged from the proxy and other online nodes' cache by expiration. Transitions to/from standby state may also be indicated by broadcast messages.

An online node can be in one of four states (Figure 2). Every node initially goes online as a non-proxy node. A proxy-capable node becomes a proxy-candidate. There may be more than one proxy-candidate at any time. When no proxy is detected, for example by absence of a service advertisement broadcast or at the exit of a proxy, the first proxy-candidate to issue the proxy bootstrap becomes the proxy. A vacating proxy may transfer its cache to the new proxy, or the new proxy may collect advertisements from online nodes through the bootstrap. Nodes which are in standby state during the proxy change may be polled by the new proxy after the standby node transitions to online.

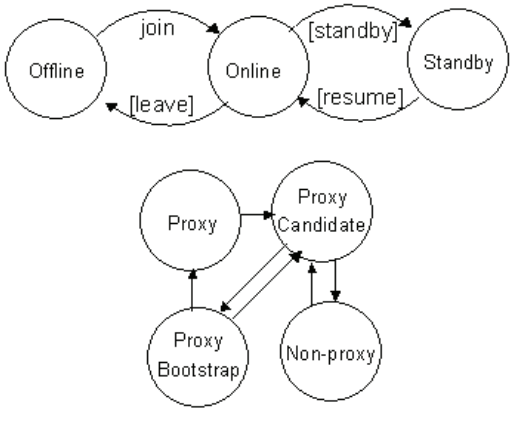
Sleeper uses property-based peer trust to secure service discovery operations. In property-based or credential-based trust (Hess et al., 2002; Seamons, Winslett, & Yu, 2001), each party has a set of certified attributes (e.g., credit card numbers, employee ID) that are exchanged to establish mutual trust. The typical components of a mechanism to provide property-based trust include:

- Trust negotiation protocol
- Trust negotiation policies
- Credentials

A method for trust negotiation has been defined for client-server context (Hess et al., 2002; Seamons et al., 2001). In this design, access control policies determine which credentials, services, and policies should be disclosed during a negotiation. Policies and credentials are secured locally at each node but are disclosed during negotiation to the remote party. Sleeper nodes establish mutual trust using the trust negotiation mechanism defined in Buford, Park, and Perkins (2006). Assuming that each peer caches public keys for certificate issuers that are relevant to its peer trust policies, then peer trust establishment can be performed without a centralized authority. A service discovery mechanism is *privacy preserving*, if a peer can discover the service description using the mechanism only if the peer satisfies the criteria C. Thus a mechanism that only distributes service descriptions to peers which are members of group G with criteria C is privacy preserving. Sleeper uses trust negotiation to create groups of peers that satisfy membership criteria C. Group management is provided by a group service (GS) that is available at every peer. The GS caches private service descriptions for each group and allows only group members to retrieve them. The GS publishes encrypted service descriptions that can only be decrypted by members of G. These encrypted service descriptions are broadcasted to all connected peers, but can only be decrypted by group members.

The secure agent technology (Buford, Park, et al., 2006) used in Sleeper for trust negotiation can also be used for enabling trust in service composition (Buford, Kumar, & Perkins, 2006).

Figure 2. Sleeper node states and state transitions; online nodes can be in one of four states (Buford et al., 2006)



SSRD

With a view to ensure enhanced security through a lightweight solution for resource discovery in pervasive environment, simple and secure resource discovery (SSRD) has been proposed by the researchers in Sharmin et al. (2006a). The fundamental part of the solution is a trust–based, service-oriented adaptive security mechanism built on middleware adaptability for resource discovery, knowledge usability, and self-healing (MARKS), a middleware and framework developed for resource constrained pervasive devices for pervasive applications (Sharmin et al., 2006b). The SSRD unit of

Figure 3. Sleeper groups in broadcast of advertisements; symmetric keys are broadcast with public key encryption (Buford, Celebi, et al., 2006)

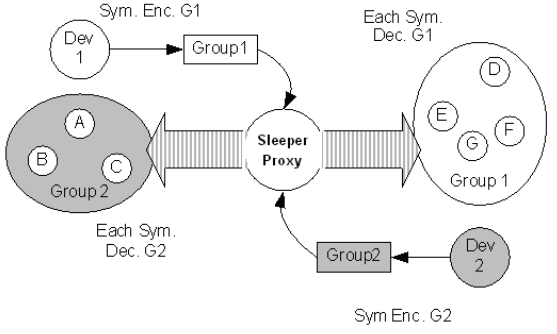
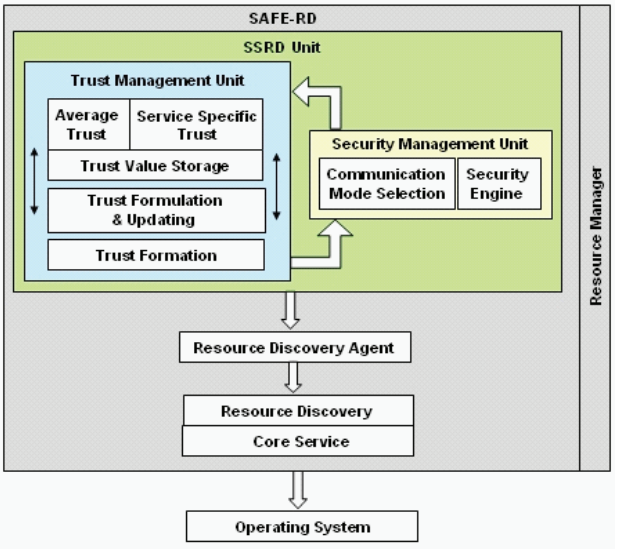


Figure 4. Resource discovery model (Sharmin et al., 2006a)



MARKS consists of *trust management* and *security management* sub units and it provides a resource discovery agent (Figure 4).

The *trust management unit* is responsible for maintaining trust relationships with other devices. It calculates trust values for the relationships between devices and also updates the trust values depending on the behavior of the service provider or requester. It maintains a list of service-specific average trust values and communicates to the security management unit whenever necessary. Trust values are quantified in the range of 0.0 to 1.0 to represent the degree of trustworthiness of a node. Complete trust and complete distrust are represented by 1.0 and 0.0 respectively. A new device with no prior interaction record is assigned a value of 0.5, which indicates a neutral condition. The dynamic property trust evolves over time and may possess the asymmetric transitive property depending on services. Each owner or manager of a device retains a table that indicates the security level (ranging from 1 to 10) required by each of the available services or applications. The resource manager consults "Service-trust" for all the neighboring nodes to decide whether the service could be provided. For example, for services with security level < 5, no trust calculation or secure communication is needed. For services with higher security levels, initially trust is calculated and then secure communication is established between the provider and the requester. This lessens both the computation cost and the communication overhead.

Trust models are designed to associate each device with a trust value based on past behavior with the requesting device. Also when we calculate a trust value for an unknown device, we consider the PGP (Zimmermann, 1995) based trust model. PGP is based on mutual certification of the validity of the keys. In case a new device joins the network or a device that never communicated with a service-providing device, the service providing device generates a multicast message to all devices that it has interacted with and asks for their recommendation about this device. From the recommendations the trust value is calculated for that service. The issue with dynamic update of trust values has been addressed more clearly with specific situations in the researchers' enhanced adaptation of this model named SSRD+ (Sharmin, Ahmed, & Ahamed, 2006c).

FUTURE RESEARCH

The open and dynamic nature of the pervasive computing environment requires a security mechanism

that is unobtrusive to the user and makes it possible to securely provide and discover the services available for the user in a transparent manner. Some of the open issues regarding challenges in secure and private service discovery are highlighted in this section.

Privacy

Although contextual information plays a pivotal role in dynamic pervasive environments, it may also expose private information. When granting access to a service, a person's context information like location, time, and activity can be exposed. Further, policies and constraints are themselves subject to privacy protection. Private information management, such as the recursive constraint based security model in Hengartner and Steenkiste (2006), is one approach to prevent direct information leakage. However, such mechanisms are generally susceptible to attacks involving collusion and inference.

In a context- and location-sensitive medical application, researchers developed a system for practitioners to easily share context in their work tasks. Subsequently, questions of privacy led the designers to limit access to this information. As another example, the Gaia project has shown a privacy preserving hop by hop routing algorithm that carries information about the location of the user but does not reveal the exact location or identity of the user. Thus the privacy level and willingness of disclosure of personal information varies depending on information type, collection method, time, and other factors. In some scenarios users are reluctant to disclose identity information but do not care about location information. The situation might be reversed in other cases. Formulation of policies that are understood and can be managed by users is an important goal.

Trust

As discussed earlier, a key element for secure service discovery in ad hoc environments is the ability to establish a level of trust betweens peers. The trust life cycle can be narrated in short as trust formation, evolution, and exploitation. In general, trust is formed by experience through earlier interactions, verifiable properties of each party, recommendations from trusted entities, and reputation in a community. The challenges faced during trust establishment are due to the absence of a global trust framework, the large number of autonomous and anonymous entities, the large number of domains, and different trust requirements for large number of application contexts.

Recent context-aware trust models focus on dynamic trust values, which are updated over time and distance and incorporate behavioral models for evolution of trust. Risk analysis maps each action to possible outcomes associated with a cost/benefit. Decisions consider the likelihood of the risk and cost. Unresolved issues in trust establishment include detecting and prevent collusion, managing the trade-off between privacy and property disclosure, and efficient trust mechanisms in large communities.

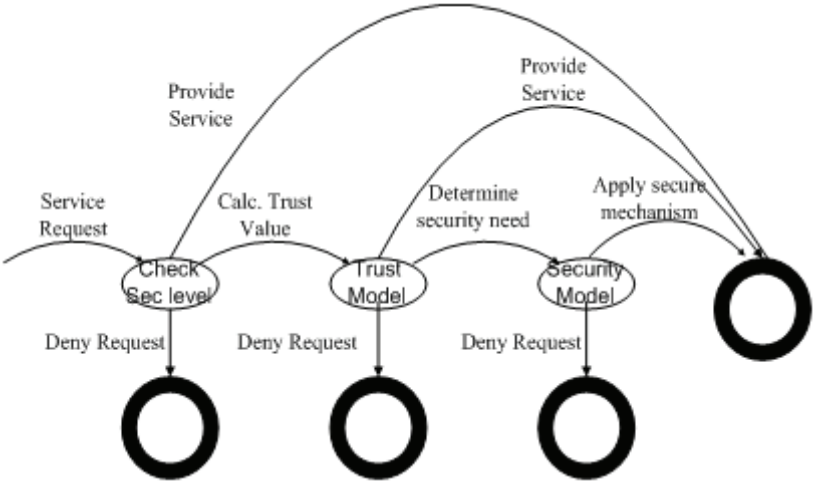
Multi-Protocol Environments

The combination of multi-homed mobile devices and multiple service discovery protocols means that service access may cross not only administrative boundaries but also different service discovery domains with varying security properties. As an example, a mobile device may include protocol support for Bluetooth, SLP, and UPnP. Then the device can easily discover services in different domains that it roams to, if these domains use different service discovery protocols. As a multi-home device, it may simultaneously connect to domains with different service discovery protocols.

As a second example, a single user may have a set of personal mobile devices configured in a PAN. These devices can use the PAN security mechanism for security and privacy control, and identity-based authentication for mutual trust. The PAN may support a specific service discovery protocol. One or more of the devices in the PAN may also connect to outside networks with different service discovery protocols and security mechanisms.

These types of scenarios indicate that future mobile devices may need to operate in multiple

Figure5. Conceptual diagram of SSRD model (Sharmin et al., 2006b)



security contexts. In these cases there is the potential for conflicting access policies and unanticipated information flows between different regions. Further, there are challenges in managing groups across domains and mapping service semantics and identities between different domains.

Trust in Service Composition

A device in a pervasive computing environment may offer a service to other devices. The service may be aggregated from services offered by other devices. By aggregating service facilities across devices, a collection of limited-resource devices may be able to offer services that would otherwise not be available. However, devices which invoke or participate in these services may be concerned about the integrity and trustworthiness of the various components that are combined to provide these services. Existing service discovery mechanisms do not expose such nested or recursive relationships when a service is offered or invoked.

Conventional methods for assuring trustworthiness of software components are typically used to convey trustworthiness to the end user or developer. They provide no explicit representation of trust between distributed components. Further, these methods do not explicitly validate composite services that may be created from different service sources. Composition trust bindings (Buford, Kumar, et al., 2006) are one approach for providing trust in both control and data paths in peer-to-peer service composition.

CONCLUSION

The general availability of broadband-wireless-enabled devices is a key catalyst in enabling many powerful peer-to-peer usage patterns, which have been described as pervasive computing. However, these usage scenarios will frequently involve devices which are outside a single secure administrative boundary and may include ad hoc interactions where no prior trust relationship exists. Further, there is significant variation in basic authentication, authorization, and privacy mechanisms offered in wireless networks. Consequently many existing designs for service discovery have insufficient security, privacy, and trust support.

Assuming that most wireless networks will in the future provide encrypted transmission, user/device authentication, and authorization control in a given administrative domain, there remain important security related questions for service discovery in cross-domain cases, in ad hoc

cases, and when the devices/users are not a priori mutually authenticated. Consequently, we do not expect that improvements in the security of wireless networks, while important, will be sufficient to address all the requirements identified here for secure service discovery.

Toward this end, after surveying a variety of approaches to secure service discovery today, we presented case studies of two recent service discovery protocols, which include trust establishment mechanisms to enable trust between a priori untrusted devices and peers. We also provided a summary of future research directions.

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KEY TERMS

Context: Context is the location, time, and activity state of the user when performing a service-related operation such as discovery, advertisement, or invocation.

Federated Discovery: Federated discovery is a service discovery mechanism that incorporates two or more different service advertisement mechanisms.

Meta Discovery: Meta discovery is the discovery of a service discovery mechanism by using meta information about that mechanism (Buford, Brown et al., 2006).

Peer Trust: Peer trust is the degree to which a peer device is willing to disclose information or provide access to resources to another peer, and

which may be determined by experience through earlier interactions, verifiable properties of each party, recommendations from trusted entities, and reputation in a community.

Pervasive Computing: Pervasive computing is the evolution of distributed computing in which networked computing devices are integrated throughout the personal and work environments in a connected way, also referred to as ubiquitous computing.

Secure Service Discovery: Secure service discovery is service discovery that enforces privacy and security policies of the devices participating in the service location process.

Service Composition: Service composition is the ability to dynamically discover and combine component services to form new services.

Service Discovery: Service discovery occurs when device resources and functions are packaged as services, in a networked environment, and a device finds another device capable of offering a specific service or resource.

Chapter III
Security of Mobile Code

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ABSTRACT

The recent development in the mobile technology (mobile phones, middleware, wireless networks, etc.) created a need for new methods of protecting the code transmitted through the network. The oldest and the simplest mechanisms concentrate more on integrity of the code itself and on the detection of unauthorized manipulation. The newer solutions not only secure the compiled program, but also the data, that can be gathered during its "journey," and even the execution state. Some other approaches are based on prevention rather than detection. In this chapter we present a new idea of securing mobile agents. The proposed method protects all components of an agent: the code, the data, and the execution state. The proposal is based on a zero-knowledge proof system and a secure secret sharing scheme, two powerful cryptographic primitives. Next, the chapter includes security analysis of the new method and its comparison to other currently more widespread solutions. Finally, we propose a new direction of securing mobile agents by straightening the methods of protecting integrity of the mobile code with risk analysis and a reputation system that helps avoiding a high-risk behavior.

INTRODUCTION

A software agent is a program that can exercise an individual's or organization's authority, work autonomously toward a goal, and meet and interact with other agents (Jansen & Karygiannis, 1999). Agents can interact with each other to negotiate contracts and services, participate in auctions, or barter. Multi-agent systems have sophisticated applications, for example, as management systems for telecommunication networks or as artificial intelligence (AI)-based intrusion detection systems. Agents are commonly divided into two types:

- Stationary agents
- Mobile agents

The stationary agent resides at a single platform (host), the mobile one can move among different platforms (hosts) at different times.

The mobile agent systems offer new possibilities for the e-commerce applications: creating new types of electronic ventures from e-shops and e-auctions to virtual enterprises and e-marketplaces. Utilizing the agent system helps to automate many e-commerce tasks. Beyond simple information gathering tasks, mobile agents can take over all tasks of commercial transactions, namely, price negotiation, contract signing, and delivery of (electronic) goods and services. Such systems are developed for diverse business areas, for example, contract negotiations, service brokering, stock trading, and many others (Corradi, Cremonini, Montanari, & Stefanelli, 1999; Jansen & Karygiannis, 1999; Kulesza & Kotulski, 2003). Mobile agents can also be utilized in code-on-demand applications (Wang, Guan, & Chan, 2002). Mobile agent systems have advantages even over grid computing environments:

- Require less network bandwidth
- Increase asynchrony among clients and servers
- Dynamically update server interfaces
- Introduce concurrency

The benefits from utilizing the mobile agents in various business areas are great. However, this technology brings some serious security risks; one of the most important is the possibility of tampering with an agent. In mobile agent systems the agent's code and internal data autonomously migrate between hosts and can be easily changed during the transmission or at a malicious host site. The agent cannot itself prevent this, but different countermeasures can be utilized in order to detect any manipulation made by an unauthorized party. They can be integrated directly into the agent system, or only into the design of an agent to extend the capabilities of the underlying agent system.

Several degrees of agent's mobility exist, corresponding to possibilities of relocating code and state information, including the values of instance variables, the program counter, execution stack, and so forth. The mobile agent technologies can be divided in to two groups:

- **Weakly mobile:** Only the code is migrating; no execution state is sent along with an agent program
- **Strong mobile:** A running program is moving to another execution location (along with its particular state)

The protection of the integrity of the mobile agent is the most crucial requirement for the agent system. The agent's code and internal data autonomously migrate between hosts and can be easily changed during the transmission or at a malicious host site. A malicious platform may make subtle changes in the execution flow of the agent's code; thus, the changes in the computed results are difficult to detect. The agent cannot itself prevent this, but different countermeasures can be utilized in order to detect any manipulation made by an unauthorized party. They can be integrated directly into the agent system, or only into the design of an agent to extend the capabilities of the underlying agent system. However, the balance between the security level and solution implementation's cost, as well as performance impact, has to be preserved. Sometimes, some restrictions of agent's mobility may be necessary.

Accountability is also essential for the proper functioning of the agent system and establishing trust between the parties. Even an authenticated agent is still able to exhibit malicious behavior to the platform if such a behavior cannot later be detected and proved. Accountability is usually realized by maintaining an audit log of security-relevant events. Those logs must be protected from unauthorized access and modification. Also the non-repudiability of logs is a huge concern. An important factor of accountability is authentication. Agents must be able to authenticate to platforms and other agents and vice versa. An agent may require different degrees of authentication depending on the level of sensitivity of the data.

The accountability requirement needs also to be balanced with an agent's need for privacy. The platform may be able to keep the agent's identity secret from other agents and still maintain a form of revocable anonymity where it can determine the agent's identity if necessary and legal. The

security policies of agent platforms and their auditing requirements must be carefully balanced with agent's privacy requirements.

Threats to security generally fall into three main classes: (1) disclosure of information, (2) denial of service, and (3) corruption of information (Jansen, 1999). Threats in agent system can be categorized with regard to agents and platform relations (e.g., agent attacking an agent, etc.). Another taxonomy of attacks in agent system was proposed in Man and Wei (2001). The article describes two main categories of attacks: purposeful and frivolous. The first kind is carefully planned and designed and can be further classified by the nature of attack (read or non-read) and number of attackers (solo or collaborative). During the second kind of attacks, the attacker may not know the effect of his/her actions or gain an advantage. These attacks can be random or total. Another category of attacks is connected with traffic analysis (Kulesza, Kotulski, & Kulesza, 2006) or called *blocking attacks* (when a malicious platform refuses to migrate the agent), as described by Shao and Zhou (2006). In this chapter we will focus on the threats from an agent's perspective.

Among the mentioned threats, the most important are connected with the agent platform since the most difficult to ensure is the agent's code/state integrity. There are two main concepts for protecting mobile agent's integrity:

- Providing trusted environment for agent's execution
- Detection or prevention of tampering

The first group of methods is more concentrated on the whole agent system than on an agent in particular. These seem to be easier to design and implement but, as presented in Oppliger (2000), mostly lead to some problems. The assumption that an agent works only with a group of trusted hosts makes the agent less mobile than it was previously assumed. Also an agent may need different levels of trust (some information should be revealed to host while in another situation it should be kept secret). Sometimes, it is not clear in advance that the current host can be considered as trusted. A method to provide such an environment is special tamper-resistant hardware, but the cost of such a solution is usually very high.

The second group of methods provides the agents' manager with tools to detect that the agent's data or code has been modified, or an agent with a mechanism that prevents a successful, unauthorized manipulation. In this chapter we concentrate on the "built-in" solutions because they enable an agent to stay mobile in the strong sense and, moreover, provide the agent with mechanisms to detect or prevent tampering. Detection means that the technique is aimed at discovering unauthorized modification of the code or the state information. Prevention means that the technique is aimed at preventing changes of the code and the state information in any way. To be effective, detection techniques are more likely than prevention techniques to depend on legal or other social framework. The distinction between detection and prevention can be sometimes arbitrary, since prevention often involves detection (Jansen, 2000).

BACKGROUND

Many authors proposed methods for protecting integrity of the mobile code. The most interesting of them are presented in this section.

Time Limited Black-Box Security and Obfuscated Code

These methods are based on a *black-box* approach. The main idea of the black-box is to generate executable code from a given agent's specification that cannot be attacked by read (disclosure) or modification attacks. An agent is considered to be black-box if at any time the agent code cannot be attacked in the previous sense, and if only its input and output can be observed by the attacker. Since it is not possible to implement it today, the relaxation of this notion was introduced Hohl (1998): it is not assumed that *the black-box protection* holds forever, but only for a certain known time. According to this definition, an agent has the time-limited black-box property if for a certain known time it

cannot be attacked in the aforementioned sense. The *time limited black-box* fulfills two black-box properties for this limited time:

- Code and data of the agent specification cannot be read
- Code and data of the agent specification cannot be modified

This scheme will not protect any data that is added later, although the currently existing variables will be changeable. Thus, it cannot protect the state of an agent, which can change between different hosts or any data, which the agent gathered.

In order to achieve the black-box property, several conversion algorithms were proposed. They are also called obfuscating or mess-up algorithms. These algorithms generate a new agent out of an original agent, which differs in code but produces the same results.

The *code obfuscation* methods make it more complicated to obtain the meaning from the code. To change a program code into a less easy "readable" form, they have to work in an automatic and parametric manner. The additional parameters should make possible that the same original program is transformed into different obfuscated programs. The difficulty is to transform the program in a way that the original (or a similar, easily understandable) program cannot be re-engineered automatically. Another problem is that it is quite difficult to measure the quality of obfuscation, as this not only depends on the used algorithm, but on the ability of the re-engineering as well. Some practical methods of code obfuscation are described by Low (1998) and general taxonomy proposed by Coilberg, Thomborson, and Low (1997).

Since an agent can become invalid before completing its computation, the obfuscated code is suitable for applications that do not convey information intended for long-lived concealment. Also, it is still possible for an attacker to read and manipulate data and code but, as a role of these elements cannot be determined, the results of this attack are random and have no meaning for the attacker.

Encrypted Functions

The encrypted functions (EF) method is one step forward in implementing the perfect black-box security. It has been proposed initially by Sander and Tschudin (1998). Since then other similar solutions were introduced (Alves-Foss, Harrison, & Lee, 2004; Burmester, Chrissikopoulos, & Kotzanikolaou, 2000) and the method is believed to be one of the canonical solutions for preserving agent's integrity (Jansen, 2000; Oppliger, 2000).

The goal of the EF, according to Jansen (2000), is to determine a method, which will enable the mobile code to safely compute cryptographic primitives, such as digital signature, even though the code is executed in non-trusted computing environments and operates autonomously without interactions with the home platform. The approach is to enable the agent platform to execute a program assimilating an encrypted function without being able to extract the original form. This approach requires differentiation between a function and a program that implements the function.

The EF system is described as follows by Oppliger (2000):

A has an algorithm to compute function *f*. *B* has an input *x* and is willing to compute *f*(*x*) for *A*, but *A* wants *B* to learn nothing substantial about *f*. Moreover, *B* should not need interacting with *A* during the computation of *f*(*x*).

The function *f* can be, for example, a signature algorithm with an embedded key or an encryption algorithm containing the one. This would enable the agent to sign or encrypt data at the host without revealing its secret key.

Although the idea is straightforward, it is hard to find the appropriate encryption schemes that can transform arbitrary functions as shown. So far, the techniques to encrypt rationale functions and polynomials have been proposed. Also a solution based on the RSA cryptosystem was described (Burmester et al, 2000).

Cryptographic Traces

The articles by Vigna (1997, 1998) introduced cryptographic traces (also called execution traces) to provide a way to verify the correctness of the execution of an agent. The method is based on traces of the execution of an agent, which can be requested by the originator after the agent's termination and used as a basis for the execution verification. The technique requires each platform involved to create and retain a non-repudiation log or trace of the operations performed by the agent while resident there and to submit a cryptographic hash of the trace upon conclusion as a trace summary or fingerprint. The trace is composed of a sequence of statement identifiers and the platform signature information. The signature of the platform is needed only for those instructions that depend on interactions with the computational environment maintained by the platform. For instructions that rely only on the values of internal variables, the signature is not required and therefore is omitted.

This mechanism allows detecting attacks against code; state and control flow of mobile agents. This way, in the case of tampering, the agent's owner can prove that the claimed operations could never been performed by the agent. The technique also defines a secure protocol to convey agents and associated security-related information among the various parties involved, which may include a trusted third party to retain the sequence of trace summaries for the agent's entire itinerary. The approach has a number of drawbacks, the most obvious being the size and number of logs to be retained, and the fact that the detection process is triggered sporadically, based on suspicious results' observations or other factors.

Chained MAC Protocol

Different versions of chained message authentication code (MAC) protocol were described by Karjoth, Asokan, and Gulcu (1999) and Yee (1999). Some of them require existence of public key infrastructure, others are based on a single key. This protocol allows an agent to achieve strong forward integrity. To utilize this protocol, only the public key of the originator has to be known by all agent places. This can occur when the originator is a rather big company that is known by its smaller suppliers.

Assume that r_n is a random number that is generated by n^{th} host. This value will be used as a secret key in a MAC. The partial result o_n (single piece of data, generated on n host), r_n and the identity of the next host are encrypted with the public key of the originator K_{i_0}, forming the encapsulated message O_n:

$$O_n = \{r_n, o_n, id(i_{n+1})\}K_{i_0}$$

A *chaining relation* is defined as follows (here H denotes a hash-function and h denotes the digest):

$$h_0 = \{r_0, o_0, id(i_1)\}K_{i_0}$$

and

$$h_{n+1} = H\{h_n, r_n, o_n, id(i_{n+1}))$$

When an agent is migrating from host i_n to i_{n+1}:

$$i_n \rightarrow i_n{+}1 : \{O_0, ..., O_n, h_{n+1}\}$$

Similar schemes are also called *partial results encapsulation* methods (Jansen, 2000).

Watermarking

Watermarking is mainly used to protect the copyrights for digital contents. A distributor or an owner of the content embeds a mark into a digital object, so its ownership can be proven. This mark is usually secret. Most methods exploit information redundancy and some of them can also be used to protect the mobile agent's data and code.

A method of watermarking of the mobile code was proposed by Esparza, Fernandez, Soriano, Munoz, and Forne (2003). A mark is embedded into the mobile agent by using software watermarking techniques. This mark is transferred to the agent's results during the execution. For the executing

hosts, the mark is a normal part of results and is "invisible." If the owner of the agent detects that the mark has been changed (it is different than expected), he or she has proof that the malicious host was manipulating the agent's data or code. Figure 1 illustrates how the mark is appended to data during the mobile agent's computations on various hosts.

The paper by Esparza et al. (2003) presents three ways of embedding the watermark into the agent:

- Marking the code
- Marking the input data
- Marking the obfuscated code

The mark or marks are validated after the agent returns to its originator.

Possible attacks against this method include:

- **Eavesdropping:** If the data is not protected in any way (e.g., not encrypted) it can be read by every host.
- **Manipulation:** The malicious host can try to manipulate either the agent's code or data to change the results and still keep the proper mark.
- **Collusion:** A group of malicious hosts can cooperate to discover the mark by comparing the obtained results.

Fingerprinting

Software fingerprinting uses watermarking techniques in order to embed a different mark for each user. Software fingerprinting shares weaknesses with software watermarking: marks must be resilient to manipulation and "invisible" to observers.

The method for fingerprinting was proposed by Esparza et al. (2003). Contrary to the watermarking methods presented previously here, the embedded mark is different for each host. When the agent returns to the owner, all results are validated and the malicious host is directly traced (see Figure 2).

The article presents two ways of embedding the mark into the agent:

- **Marking the code:** In this case, malicious hosts have the possibility of comparing their different codes in order to locate their marks.
- **Marking the input data:** The data are usually different for each host, so it is harder to identify the mark.

The procedure is similar to the mobile agent watermarking approach. However, the owner must know each mark for each host and their location. One of the possibilities of reconstructing the marks is to catch the information about the previously chosen places in the results.

Figure 1. Example of watermarking

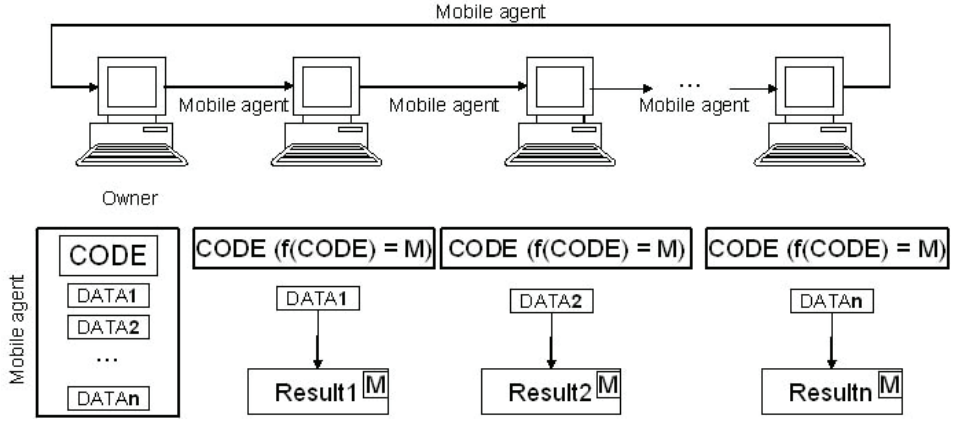
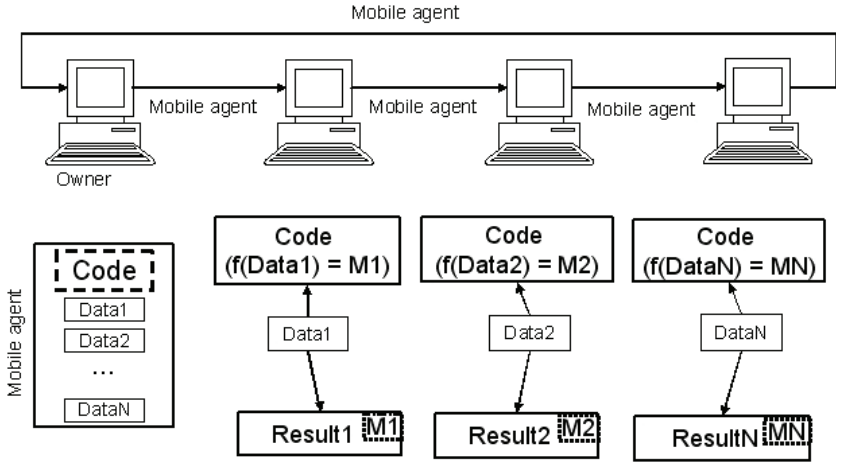


Figure 2. Example of fingerprinting



Possible attacks against this method include:

- **Eavesdropping:** If the data are not protected in any way (e.g., not encrypted) it can be read by every host.
- **Manipulation:** The malicious host can try to manipulate either the agent's code or data to change the results and still keep the proper mark.
- **Collusion:** Colluding hosts cannot extract any information about the mark comparing their data or results, because every host has a different input data and a different embedded mark.

The difference between mobile agent watermarking and fingerprinting is the fact that in the second case it is possible to detect collusion attacks performed by a group of dishonest hosts.

Publicly Verifiable Chained Digital Signatures

This protocol, proposed by Karjoth (1998) allows verification of the agent's chain of partial results not only by the originator, but also by every agent place. However, it is still vulnerable to interleaving attacks. This protocol makes it possible for every agent place, which receives an agent to verify that it has not been compromised. This saves computing power because if an agent has indeed been compromised, the agent place can reasonably refuse to execute the compromised agent.

Environmental Key Generation

This scheme allows an agent to take a predefined action when some environmental condition is true (Riordan & Schneier, 1998). The approach centers on constructing agents in such a way that upon encountering an environmental condition (e.g., via a matched search string), a key is generated, which is then used to cryptographically unlock some executable code. The environmental condition is hidden through either a one-way hash or public key encryption of the environmental trigger. This technique ensures that a platform or an observer of the agent cannot uncover the triggering message or response action by directly reading the agent's code.

Itinerary Recording with Replication and Voting

A faulty agent platform can behave similarly to a malicious one. Therefore, applying fault tolerant

capabilities to this environment should help counter the effects of malicious platforms (Schneider, 1997). One such technique for ensuring that a mobile agent arrives safely at its destination is through the use of replication and voting. Rather than using a single copy of an agent to perform a computation, multiple copies are used. Although a malicious platform may corrupt a few copies of the agent, enough replicas avoid the encounter to successfully complete the computation. A slightly different method based on multiple copies of agent was proposed by Benachenhou and Pierre (2006). In this proposal, the copy of agent is executed on a trusted platform to validate results obtained on other platforms.

A METHOD BASED ON SECRETS AND PROOFS

In the proposed system we assume that there exist at least three parties:

- A manager
- An agent
- A host

The manager can be an originator of the agent. It plays a role of a verification instance in the scheme and creates initial countermeasures for the agent. The manager also plays a role of a trusted third party.

Outline of the Method

The zero-knowledge proof systems (Goldreich, 2002) enable the verifier to check validity of the assumption that the prover knows a secret. In our system the verifier would be the manager or owner of agents and, obviously, agents would be the provers. In the initial phase, the manager computes a set of secrets. The secrets are then composed into the agent, so that if the manager asks the agent to make some computations (denote them as a function f), the result of this would be a valid secret. This function should have the following property:

- If we have x_1 and $f(x_1)$ then it is computationally infeasible to find such x_2 that $f(x_1) = f(x_2)$

If the secret is kept within an agent, then also the host can use the zero-knowledge protocol to verify it. Every authorized change of agent's state results in such a change of the secret that the secret remains valid. On the other hand, every unauthorized change leads to loosing the secret, so at the moment of verification by host or manager, the agent is not able to prove possession of a valid secret. Since the host can monitor all agent's computations, the secret should not only change with agent's execution state, but should also be different for different hosts, so one host could only validate the secret prepared for operations that should be executed at this platform. In our system the host can tamper the agent and try to make such changes that so that he/she will be still able to obtain the proper secret, but the characteristics of function f will not allow doing this. Some possible candidates for the function f can be a hash function. Our approach is a detection rather than prevention (see Zwierko & Kotulski, 2007).

Specification of the Method

The Initial Phase

The initial phase has three steps:

1. The manager computes a set of so-called identities, denoted as ***ID***. It is public. For each identity, the manager computes appropriate secret, denoted as σ. The details for generating those values depend upon chosen zero knowledge system.
2. To compose σ into an agent, any secure secret sharing scheme (Pieprzyk, Hardjono, & Seberry, 2003) with threshold t can be used. The manager creates n shares, such that the reconstructed secret would be σ. The t-1 shares are composed into an agent and the rest are distributed among the hosts via secure channels (this is illustrated in Figure 3).
3. The manager now needs to glue the shares into an agent in such a way, that when the

agent is in a proper execution state, it is able to obtain from its code/state variables the correct shares. Since the agent is nothing more than a computer program, it can be described as a *finite state machine* (FSM). Assume, we have the agent of the form $<\Sigma, S, S_I, S_F, \delta>$, where:

- Σ is the input alphabet
- $S = \{f_0, \ldots, f_n\}$ is a set of all possible states
- S_I is a subset of S with all initial states
- S_F is a subset of S with all finishing states, possibly empty
- $\delta: \Sigma \times S \rightarrow S$ is a state transition function.

Figure 4 shows an example of agent's FSM. It is obvious that only some execution states should be observed during the computation at the host platform (e.g., the ones connected with gathering and storing the data). If the state f_j is the first state of the agent's computations at the host platform, then it is natural that the shares should be generated only from this state. Additionally, some internal variables that differ for each host should be utilized to obtain different secrets for each host. Thus, to create agent's shares, $f_j, c_i \in \Sigma$, and the code should be used.

In other cases, where the pair f_j and c_i is not unique for each host, the previous states or other data should be used. It should be possible to obtain the proper shares for current host based on appropriate execution state and internal variables. If there is more than one unique combination of (f_j, c_i) for one host, then for each of them the host should obtain an ID and a share. The agent's code (in a certain form) should be a part of the data that are required to recreate the secret to enable detection of every unauthorized manipulation, which could be performed by previous host.

To create the shares from the mentioned data, the hash function or an encryption function with the manager's public key can be used.

The Validation Phase

1. The host, which wants to verify an agent's integrity, sends its share to the agent.

Figure 3. Distributing ID and shares to hosts

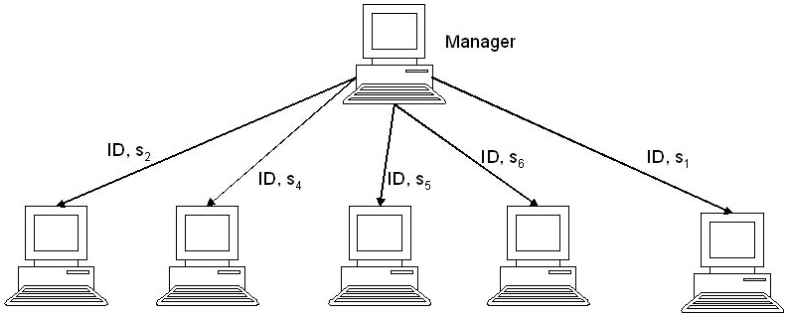
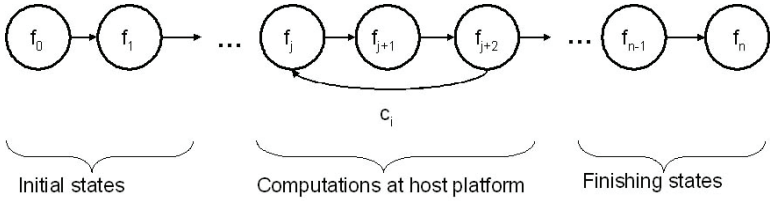


Figure 4. Mobile agent as an FSM



2. The agent creates the rest of the shares from its code and the execution state. It recreates the secret. The agent computes the secret σ and uses it for the rest of the scheme, which is a zero-knowledge identification protocol.
3. The agent and the host execute the selected zero-knowledge protocol, so that the host can confirm the correctness of σ.

The manager can compute many identities, which may be used with different execution states. In that situation the agent should first inform host which identity should be used, or the host can simply check the correctness of σ for all possible identities.

SECURITY AND SCALABILITY

Definitions and Notions

This section presents basic notions concerning agent's integrity that will be later used in description of the selected solutions. The integrity of an agent means that an unauthorized party cannot change its code or execution state, or such changes should be detectable (by an owner, a host or an agent platform, which want to interact with the agent). The authorized changes occur only when the agent has to migrate from one host to another. Next is a more formal definition:

Definition 1 (integrity of an agent). An agent's integrity is not compromised if no unauthorized modification can be made without the agent's owner noticing this modification.

The concept of forward integrity is also used for evaluation of many methods (Karjoth et al., 1999; Yee, 1999). This notion is used in a system where agent's data can be represented as a chain of partial results (a sequence of static pieces of data). Forward integrity can be divided into two types, which differ in their possibility to resist cooperating malicious hosts. The general goal is to protect the results within the chain of partial results from being modified. Given a sequence of partial results, the forward integrity is defined as follows:

Definition 2 (Karjoth et al., 1999; Yee, 1999). The agent posses the weak forward integrity feature if the integrity of each partial result m0, …, mn-1 is provided when in is the first malicious agent place on the itinerary.

Weak forward integrity is conceptually not resistant to cooperating malicious hosts and agent places that are visited twice. To really protect the integrity of partial result, we need a definition without constraints.

Definition 3 [strong forward integrity (Karjoth et al., 1999)]. The agent system preserves strong forward integrity of the agent if none of the agent's encapsulated messages mk, with k < n, can be modified without notifying the manager.

In this chapter we refer to forward integrity as to strong forward integrity (when applicable). To make notion of forward integrity more useful, we define also publicly verifiable forward integrity, which enables any host to detect compromised agents:

Definition 4. The agent posses the publicly verifiable forward integrity if every host in can verify that the agent's chain of partial results mi0 ,…, min has not been compromised.

The other important notion concerning agent's integrity, a concept of black-box security (Hohl, 1998) was introduced in the Time Limited Black-Box Security and Obfuscated Code section.

Analysis

The proposed scheme should be used with more that one identity. This would make it very hard to manipulate the code and the data. The best approach is to use one secret for each host. We assume that the malicious host is able to read and manipulate an agent's data and code. He/she can try to obtain from an agent's execution state the proper shares. The host can also try to obtain a proper secret and manipulate the agent's state and variables in a way that the obtained secret would

stay the same. But the host does not know other secrets that are composed into the agents; also he/she does not know more shares to recreate those secrets, so, any manipulation would be detected by the next host.

The protocol is not able to prevent any attacks that are aimed at destroying the agent's data or code, meaning that a malicious host can "invalidate" any agent's data. But this is always a risk, since the host can simply delete an agent.

- **Weak forward integrity:** The proposed method posses the *weak forward integrity* property: the malicious host cannot efficiently modify previously generated results.
- **Strong forward integrity:** The protocol provides the agent also with *strong forward integrity*, because the host cannot change previously stored results (without knowledge of secrets created for other hosts). He/she cannot also modify the agent in a way that could be undetectable by the next host on the itinerary or by the owner.
- **Publicly verifiable forward integrity:** Each host can only verify if the agent's code or the execution state has not been changed. They cannot check wherever the data obtained on other platforms has not been modified. The agent's owner, who created all secrets, can only do this.
- **Black-box security:** The proposed system is not resistant to read attacks. A malicious host can modify the code or data, but it is detectable by agent's owner, so it is resistant to manipulation attack. The system does not have full black-box property.

Comparison with Other Methods

It is a difficult task to compare systems based on such different approaches as presented here. We decided to split comparison into two categories:

- **Practical evaluation:** If the method is hard or easy to implement:
  - **Hard:** No practical implementation exists at the moment
  - **Medium:** The method has been implemented, with much effort
  - **Easy:** The method is widely used and has been implemented for different purposes

  and what elements of an agent it protects:
- **Theoretical evaluation:** If the method satisfies the security definitions from the *Definitions and Notions* section.

The theoretical evaluation is quite hard, because some methods that have the black-box property do not "fit" other definitions. If the code or data cannot be read or manipulated (the ideal case), then how we can discuss if it can be verifiable, or, if it fulfills the forward integrity.

As for evaluation of the black-box property, it is very hard to provide the code that cannot be read. In all cases, marked by *, (see Table 2) the adversary can modify the agent but not in a way that owner or other host would not notice. This means that no efficient manipulation attack can be made, so one part of the black-box property is satisfied.

In # case the *publicly verifiable forward integrity* is satisfied only partially, because the agent's code can be verified but the data cannot.

Scalability

The initialization phase. The first phase is similar to the bootstrap phase of the system. The hosts and the manager create a static network. It is typical for agents' systems that the manager or the owner of an agent knows all hosts, so distribution of all IDs and shares is efficient. We can compare this to sending a single routing update for entire network as in OSPF protocol (the flooding). Whenever a new agent is added to the system, the same amount of information to all hosts has to be sent. Since the messages are not long (a single share and few IDs) and are generated only during creating a new agent, that amount of information should not be a problem. The sizes of parameters (keys lengths, number of puzzles, and number of shares) are appropriately adjusted to the agents' network size.

The operating phase. During the validation phase no additional communication between the manager and the hosts is required.

Table 1. Practical comparison of the integrity protection methods

Method	Implementation	Protects code	Protects data	Protects execution state
Encryption functions	Hard	Yes	Yes	No
Obfuscated code	Medium	Yes	No	No
Cryptographic traces	Hard	Yes	No	Yes
Watermarking	Easy	Yes	Yes	No
Fingerprinting	Easy	Yes	Yes	No
Zero knowledge proof	Easy	Yes	Yes	Yes

Table 2. Theoretical comparison of integrity protection methods

Method	Weak forward integrity	Strong forward integrity	Publicly verifiable forward integrity	*Black-box* property
Encryption functions	No	No	No	Yes
Obfuscated code	Yes	Yes	No	Partially*
Cryptographic traces	Yes	Yes	Yes	No
Watermarking	Yes	No	No	Partially*
Fingerprinting	Yes	Yes	No	Partially*
Zero knowledge proof	Yes	Yes	No#	Partially*

Modifications

A similar scenario can be used to provide integrity to the data obtained by the agent from different hosts. A malicious host could try to manipulate the data delivered to the agent by the previously visited hosts. To ensure that this is not possible, the agent can use the zero-knowledge protocol to protect the data. For each stored piece of data, the agent can create a unique "proof," utilizing the zero-knowledge protocol. Any third party, who does not possess σ, is not able to modify the proof. So the manager knowing σ can be sure that the data was not manipulated.

An area for development of the proposed integrity solution is to find the most appropriate function for composing secrets into hosts: The proposed solution fulfills the requirements, but some additional evaluation should be done. The next possibility for the future work would be to integrate the proposed solution to some agents' security architecture, possibly the one that would also provide an agent with strong authentication methods and anonymity (Zwierko & Kotulski, 2005). Then, such a complex system should be evaluated and implemented as a whole. A good example of such a system would be an agent-based electronic elections system for mobile devices, where the code integrity together with the anonymous authentication is crucial for correctness of the system (Zwierko & Kotulski, in press).

FUTURE TRENDS

In this chapter we presented methods of protection of mobile agents against attacks on their integrity. The methods offer protection on a certain level, but

the agents' security can be significantly increased by avoiding risky behavior, especially visiting suspicious hosts. This can be done by using mechanisms built into individual agents or by distributed solutions based on cooperation of agents and hosts. The most promising solutions for improvement of the mobile code security can be based on risk analysis or on reputation systems. The first one needs some built-in analysis tools while the second one requires trust management infrastructure.

Risk analysis is one of the most powerful tools used in economics, industry, and software engineering (Tixier, Dusserre, Salvi, & Gaston, 2002). Most of the business enterprises carry out such an analysis for all transactions. The multi-agent or mobile agent system can be easily compared with such an economic-like scenario: There are a lot of parties making transactions with other parties. The risk analysis could be utilized to estimate how high is the probability that selected agent platform is going to harm the agent. The biggest advantage of this solution is lack of any form of cooperation between different managers: Everyone can make its own analysis based on gathered knowledge. However, the cooperation between different managers can benefit in better analysis.

Reputation systems (Sabater & Sierra, 2005; Zacharia & Maes, 2000) are well known and utilized in different applications, especially in peer-to-peer environments. They enable the detection of malicious parties based on their previous behavior, registered, valuated, and published. We can imagine an agent system where managers and owners of agents would also rate agent platforms based on their previous actions towards the agents. Of course, such a system still requires some integrity protection mechanisms, which could be used to verify if results obtained by the agent are correct. However, the applied mechanism can be rather simple, not as complicated as some presented methods, for example, EFs.

CONCLUDING REMARKS

Among security services for stored data protection two are the most important: availability and integrity. The data unavailable is useless for a potential user. Also, the data illegally defected or falsified is a worthless source of information. No other protection has sense if the data's content is destroyed. In the case of executables we face analogous problems. Except others, the executables must be available and protected against falsification (that is unauthorized changes of the designed functioning, internal state and the carried data). The problem of availability has been successfully solved by a concept of mobile agents that simply go to the destination place and work in there. However, this solution made the problem of integrity of the mobile code or mobile agent even more important than in the case of the stored data. The falsified mobile agent is not only useless. It can be even harmful as an active party making some unplanned actions. Therefore, preserving agents' integrity is a fundamental condition of their proper functioning.

In this chapter we made an overview of the existing protocols and methods for preserving the agent's integrity. The basic definitions and notions were introduced. The most important mechanisms were presented and discussed. We also proposed a new concept for detection of the tempering of an agent, based on a zero-knowledge proof system. The proposed scheme secures both, an agent's execution state and the internal data along with its code. For the practical implementation the system requires some additional research and development work, but it looks to be a promising solution to the problem of providing an agent with effective and strong countermeasures against attacks on its integrity.

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KEY TERMS

Agent Platform (Host): Agent platform is a computer where an agent's code or program is executed. The software agent cannot perform its actions outside hosts. The host protects agents against external attacks.

Cryptographic Protocol: Cryptographic protocol is a sequence of steps performed by two or more parties to obtain a goal precisely according to assumed rules. To assure this purpose the parties use cryptographic services and techniques. They realize the protocol exchanging tokens.

Intelligent Software Agent: Intelligent software agent is an agent that uses artificial intelligence in the pursuit of its goals in contacts with hosts and other agents.

Mobile Agent: Mobile agent is an agent that can move among different platforms (hosts) at different times while the **stationary agent** resides permanently at a single platform (host).

Security Services: Security services guarantee protecting agents against attacks. During agent's transportation the code is protected as a usual file. At the host site, the agent is open for modifications and very specific methods must be applied for protection. For the agent's protection the following security services can be utilized:

- **Confidentiality:** Confidentiality is any private data stored on a platform or carried by an agent that must remain confidential. Mobile agents also need to keep their present location and the whole route confidential.
- **Integrity:** Integrity exists when the agent platform protects agents from unauthorized modification of their code, state, and data and ensure that only authorized agents or processes carry out any modification of the shared data.
- **Accountability:** Accountability exists when each agent on a given platform must be held accountable for its actions: must be uniquely identified, authenticated, and audited.
- **Availability:** Availability exists when every agent (local, remote) is able to access data and services on an agent platform, which responsible to provide them.

- **Anonymity:** Anonymity is when agents' actions and data are anonymous for hosts and other agents; still accountability should be enabled.

Software Agent: Software agent is a piece of code or computer program that can exercise an individual's or organization's authority, work autonomously at host toward a goal, and meet and interact with other agents.

Strong Mobility: Strong mobility of an agent means that a running program along with its particular (actual) state is moving from one host site to another.

Weak Mobility: Weak mobility of an agent means that only the agent's code is migrating and no execution state is sent along with an agent program.

Chapter IV
Identity Management

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ABSTRACT

The broad aim of identity management (IdM) is to manage the resources of an organization (such as files, records, data, and communication infrastructure and services) and to control and manage access to those resources in an efficient and accurate way. Consequently, identity management is both a technical and process-orientated concept. The concept of IdM has begun to be applied in identities-related applications in enterprises, governments, and Web services since 2002. As the integration of heterogeneous wireless networks becomes a key issue in towards the next generation (NG) networks, IdM will be crucial to the success of NG wireless networks. A number of issues, such as mobility management, multi-provider and securities require the corresponding solutions in terms of user authentication, access control, and so forth. IdM in NG wireless networks is about managing the digital identity of a user and ensuring that users have fast, reliable, and secure access to distributed resources and services of an next generation network (NGN) and the associated service providers, across multiple systems and business contexts.

INTRODUCTION

The broad aim of identity management (IdM) is to manage the resources of an organisation (such as files, records, data, and communication infrastructure and services) and to control and manage access to those resources in an efficient and accurate way (which in part usually involves a degree of automation). Consequently, IdM is both a technical and process-orientated concept.

The concept of IdM has begun to be applied in identities-related applications in enterprise, governments, and Web services since 2002. As the integration of heterogeneous wireless networks becomes a key issue in the fourth generation (4G) wireless networks, IdM will become crucial to the success of next generation (NG) wireless networks. A number of issues, such as mobility management, multi-provider, and securities require the corresponding solutions in terms of user authentication, access control, and so forth. Although IdM processes require the integration into existing business processes at several levels (Titterington, 2005), it remains an opportunity for NG wireless networks.

IdM in NG wireless networks is about managing the digital identity of a user and ensuring that users have fast, reliable, and secure access to distributed resources and services of NG wireless networks and associated service providers across multiple systems and business contexts.

Definition

Given the open and currently non-standardised nature of IdM, there are varying views as to the exact definition of IdM. These include:

By HP (Clercq & Rouault, 2004)
Identity Management can be defined as the set of processes, tools and social contracts surrounding the creation, maintenance, utilization and termination of a digital identity for people or, more generally, for systems and services to enable secure access to an expanding set of systems and applications.

By Reed (2002)
The essence of Identity Management as a solution is to provide a combination of processes and technologies to manage and secure access to the information and resources of an organisation while also protecting users' profiles.

By Cisco Systems (2005)
Businesses need to effectively and securely manage who and what can access the network, as well as when, where, and how that access can occur...lets enterprises secure network access and admission at any point in the network, and it isolates and controls infected or unpatched (sic) devices that attempt to access the network.

Objectives

As IdM can be used in different areas such as enterprise, government, Web services, telecommunication networks and so forth, its objectives diversity in different contexts. Generally, the IdM system is expected to satisfy the following objectives (Reed, 2002):

- It should define the identity of an entity (a person, place, or thing).
- It should store relevant information about entities, such as names and credentials, in a secure, flexible, customisable store.
- It should make the information accessible through a set of standard interfaces.
- It should provide a resilient, distributed, and high performance infrastructure for identity management.
- It should help to manage relationships between the enterprise and the resources and other entities in a defined context.

Main Aspects

Authentication

Authentication is the process by which an entity provides its identity to another party, for example, by showing photo ID to a bank teller or entering a password on a computer system. This process is broken down into several methods which may involve something the user knows (e.g., password), something the user has (e.g., card), or something the user is (e.g., fingerprint, iris, etc.). Authentication can take many forms, and may even utilise combinations of these methods.

Authorisation

Authorisation is the process of granting access to a service or information based on a user's role in an organisation. Once a user is authenticated, the system then must ensure that a particular user has access to a particular resource.

Access Control

Access control is used to determine what a user can or cannot do in a particular context (e.g., a user may have access to a particular resource/file, but only during a certain time of day, e.g., work hours, or only from a certain device, e.g., desktop in the office).

Auditing and Reporting

Auditing and reporting involves creation and keeping of records, whether for business reasons (e.g., customer transactions), but also providing a "trail" in the event that the system is compromised or found faulty.

DIGITAL IDENTITY

What is Digital Identity?

In a business transaction, identity is used to establish a level of trust upon which business can be conducted. Trust in this context is the confidence that each party they are dealing with is who he/she claims to be. Traditionally, such trust was established with the use of an observable physical attribute of an entity. For example, business dealings were in person (appearance), on the phone (voice), or with the use of signatures on contracts (handwriting).

The identity of an individual is defined as the set of information known about that person (Pato & Rouault, 2003). For example, an identity in the real world can be a set of names, addresses, driver's licenses, birth certificate, and so forth.

With the development and widespread use of digital technologies, entities have been able to communicate with each other without being physically present. In some cases, the first meeting and possibly the entirety of the transaction between two parties is held over a digital medium. There is a growing need for trust to be established in transactions over the digital world.

Digital identity is the means that an entity can use to identify themselves in a digital world (i.e., data that can be transferred digitally, over a network, file, etc.). The aim of digital identity is to create the same level of confidence and trust that a face to face transaction would generate.

Composition of Digital Identity

A digital identity seeks to digitise an individual's identity to the extent that they cannot be mistaken for someone else and that it is difficult for another person to impersonate that individual. In a typical face to face situation, identity comprises of two parts: the actual identity of the entity (something that can be observed by human senses) and the credentials or what they use to prove their identity. In Reed (2002), the attributes of digital identity are given as follows:

Who You Are
"Who you are" is the attribute that in a real world context uniquely identify a single entity. These can include knowledge or data that is only known by that entity, unique physical characteristics of that entity, or items that the entity has.

Context
Context can refer to the type of transaction or organisation that the entity is identifying itself as well as the manner that the transaction is made. Different constraint on digital identity may be enforced depending on the context. For example, the sensitive transactions related to birth certificate information over phone or internet may be prohibited.

Profile
A profile consists of data needed to provide services to users once their identity has been verified. A user profile could include what an entity can do, what they have subscribed to, what groups they are a member of, their selected services, and so forth. The profile of a user will change during the course of interaction with a service provider.

Of particular consideration is the concept of "context." Depending on the context, we differ in the actions that we are able to do as individuals. In an Internet shopping context, we may only be able to browse or purchase items. In a corporate context, it may enable us to access files or otherwise do some other activity.

Context is also important from a digital identity context as it is likely to determine the amount and type of identity information that is needed in order for the determined level of "trust" to be available. For example, in an e-mail context, the amount of identifying information that is necessary is usually only two things: a username and password. However, with more security conscious

applications, for example, bank transactions and governmental functions, more information is usually required (e.g., birth certificates, credit card numbers, and the like).

The digital identity of an individual user forms the main focus of security threats to any IdM system. As such, there are typical measures that must be taken to ensure that digital identities are kept securely.

Usage of Digital Identity

Digital identity can be used for authentication. It is where an entity must "prove" digitally that it is the one that it claims to be. It is at this stage that the credentials of digital identity are used. The simplest form of authentication is the use of a username and corresponding password. This is known as "single factor" authentication, since only a single attribute is used to determine the identity. Stronger authentication is usually obtained by not only increasing the number of attributes that are used, but also by including different types. To add to the previous example scheme, in addition to the password, an entity could also be called upon to have a particular piece of hardware plugged in, providing a "two factor" scheme (DIGITALIDWORLD, 2005).

Once an entity is authenticated, a digital identity is used to determine what that entity is authorised to do. This is where the profile of a digital identity is required. As an example, authorisation can be seen as the difference between an "administrator" and a "user" who share the same resource (for example, a computer). Both may be authenticated to use the computer, but the actions that each may do with that resource are determined by the authorisation. Authentication attempts to establish a level of confidence that a certain thing holds true, authorisation decides what the user is allowed to do.

Accounting provides an organisation with the ability of tracking unauthorised access when it occurs. Accounting involves the recording and logging of entities and their activities within the context of a particular organisation, Web site, and so forth.

PROS AND CONS OF IDENTITY MANAGEMENT

Benefits of Identity Management

Reduce Total Cost Ownership (TCO) for All Systems

Cost reduction by IdM usually is a result of more efficient use of personnel and resources, especially with regards to the following administrative bureaucracy. Examples include (Courion, 2005):

- Reducing the costs of auditing by providing real-time verification of user access rights and policy awareness enforcement
- Eliminating account administration such as account add/move/change and calls to information security staff for digital certificate registration
- Eliminating calls of password reset (the #1 support call) to internal or outsourced help desks
- Streamlining IT operations for more efficient management and reallocation to more strategic projects
- Reducing management overhead (Reed, 2002)

Competitive Advantage Through Streamlining and Automation of Business Processes

This competitive advantage is delivered by cutting down costs in areas with a high need for unnecessary support and being able to:

- Offer users a fast, secure way to access to revenue-generating systems, applications, and Web portals (Courion, 2005)
- Provide faster response to "password reset" and "insufficient access" user lockouts, thus increasing system and data availability (Courion, 2005)
- Provide 24x7x365, unassisted self-service for the most common of help desk calls (Courion, 2005)
- Improve customer and employee service; maintain confidentiality and control of customers, suppliers, and employees (Reed, 2002)

- Reduce time for new employees to gain access to required resources for work (Reed, 2002)

Increase Data Security
Data security includes the typical protection of data from unauthorised users as well as ensuring that the data being used is kept up to date across the organisation and is safe from inadvertent or intentional tampering by unauthorised users within the organisation.

- Minimise the "security gap" that exists between the time when employees leave a company and their accounts are disabled (Courion, 2005)
- Reduce the intrusion risk due to orphaned or dormant accounts (by ex-employees or those posing as ex employees) (Courion, 2005)
- Enforce the policies of consistent account provisioning to make sure that only those who need access get access (Courion, 2005)
- Enforce consistent password policies for stronger authentication (Courion, 2005)
- Reduce security threats (e.g., human error) through policy based automation (Courion, 2005)
- Ensure accurate audit trails for intrusion prevention and security reporting (Courion, 2005)
- Provide faster response to account access requests or password reset, thus reducing the need of proliferating "superuser" privileges (Courion, 2005)
- Increase the opportunity of adopting the Public Key Infrastructure by removing the biggest barrier (Courion, 2005)
- Reduce risk of incorrect information being used (Reed, 2002)

Support Legal Initiatives and Demonstrate Compliance (Courion, 2005; Reed, 2002)
In the case of legal initiatives, IdM can be used successfully to demonstrate a systematic and effective approach to safeguarding an organisation's assets and its business partners' (customers, suppliers, contractors, clients) assets. It also presents a method of ensuring that policies are enforced away from human effort and decision making (where often the process breaks down or is ignored). In summary, it can:

- Demonstrate policy enforcement
- Proactively verify the access right of a user
- Enable policy awareness testing
- Eliminate orphaned accounts systematically
- Increase protected data privacy

Additional benefits, mainly business centric, are described in more detail by Fujitsu (Locke & McCarthy, 2002):

- **Know who everyone is in the organisations:** Applied to the larger scale of the NG wireless networks, this prevents any user from "slipping through the cracks" whether they are employees or subscribers. Typically, telecommunications providers are adept at keeping customer records, but suffer the same problems with keeping track of staff. An IdM system will enable the organisation to keep stock of all their users.
- **Accurate and consistent people data in all systems:** This is particularly relevant to the existing telecommunications providers. Although services vary, the majority of providers have some lag between the time a record is changed, compared to when that change is made into the records that the company keeps. Typically, this results in undue delays when an existing or new subscriber wishes to get access to their new services. By speeding up the process by which data on users can be updated, this reduces the delay in service provisioning and offers a more significant level of quality of service.
- **Single source of data input/storage:** This feature has already been explored as one of the benefits of an IdM system. Although a distributed system must spread the location and access points for the data that it stores, by having one central system for organising

it, any additional processing that needs to be done, particularly when bridging between two different types of systems or departments, is avoided.

In general, IdM is used to provide an efficient system that covers all users within an organisation. It promotes a single system that does the entire task rather than several systems that conflict or compete with each other.

Drawbacks of Identity Management

IdM, while bringing several advantages to an organisation, may have several applicable drawbacks. These include:

- **Single point of vulnerability:** A feature that brings both advantages and disadvantages to IdM is the central system that is used. A central IdM system is used to avoid the vulnerabilities associated with competing or incompatible systems, as well as reducing the maintenance costs involved in running different types of systems. However, the flip side to this approach is that it represents a single point of vulnerability that, if compromised, can lead to the easy breach of all the data that the system is protecting. To counter this, IdM systems generally recommend that the additional resources that are saved by the organisation employing the IdM system are re-invested into providing more effective security measures. This will result in a system that is, overall, more secure than the existing mixture of systems that individually, are not as secure.
- **Migration from legacy systems and transition costs:** IdM systems are generally at odds with existing systems that manage and secure users and resources. The concept of IdM systems involves the replacing of existing systems with a single IdM system. For larger organisations with staff and hardware that are selected based upon a preference for an existing system or systems, this represents a significant along with all the associated costs of replacing or retraining staff, introducing new equipments and the like. It will also increase the reluctance and reduce the enthusiasm of the organisation to adopt the new IdM system.
- **Specific needs depending on the organisation:** IdM systems generally need to be customised for each particular organisation that intends to use one. This is particularly true for the areas where an IdM system must support the business processes that an organisation has set up. These are usually unique to the organisation. Other areas that would require customisation from system to system include hardware requirements, the nature of the organisations' distributed systems, and so on.
- **Extensive planning, designing, and implementation required:** An IdM system must be extremely well planned, designed, and executed if it is to avoid the disadvantages that it is trying to overcome over existing approaches to enterprise management. Due to the all-encompassing and authoritative control that an IdM system will have over an organisation, it is important that any such system caters or close to the exact specifications, outlined by the organisation. Otherwise, the system may be used incorrectly, resulting in the same inefficiencies from non-IdM systems.
- **Relatively new concept, lack of uniform standard:** IdM as a standardised concept and solution is yet to be finalised. This increases the likelihood of IdM systems to still be in various stages of development, and more importantly, different levels of effectiveness. This may lead to increased maintenance or upgrades in the near future, or lead to flawed development and implementation for the early adopters of IdM systems. Both these alternatives result in an inefficient outcome compared to IdM's claims.

STANDARDS AND SOLUTIONS

A number of IdM technologies and standards have emerged for enterprise networks, government,

and Web services. The two main standard bodies to date are from the Liberty Alliance Project and the Web-Services (WS) Federation. However, the specifications produced by these organisations are mainly motivated by user profile management, single sign-on, and personalised services and do not address the requirements of NG wireless networks.

Relevant Standard Bodies

The standards organisations listed in Table 1 are involved in the development of standards for IdM.

IdM Standards

Directory Services
Directory services are considered a core part of any IdM system. The standards (with the standards body created by them) are:

- **X.500 (ISO):** Large global organisations/ governmental organisations
- **LDAP (IETF):** Core standard for systems relying on directory management
- **DSML (OASIS):** Web-orientated extending from LDAP

Web Services
Web services support IdM systems across private and public networks. They are aimed, as such, to connect heterogeneous systems. Several well known protocols, such as TCP/IP, belong here. The ones that have specific applications in IdM are:

- **SOAP (W3C, formerly Microsoft):** For transporting XML messages/remote procedure calls
- **WSDL (W3C):** Used to express the programming interface and location of a service
- **Universal Description, Discovery and Integration (UDDI):** Used to find and publish services

Security
Security protocols are used for protecting information:

- **SAML (OASIS):** XML-based security solution for Web services
- **Web Services Security (WSS) (Language):** Enhancements to SOAP protocol for security.

Federated Identity
Federated identity standards seek to standardise items that would make federated identities more feasible:

Table 1.

Standards Organisation	Area of Standards / Example Standards
Organisation for Advancement of Structured Information Standards (OASIS)	Private, worldwide organisation for XML standards. For example, Security Assertion Markup Language (SAML)
Web Services Interoperability (WS-I)	"Open, industry organisation to promote Web service interoperability across operating systems and programming languages" For example, Simple Object Access Protocol (SOAP)
World Wide Web Consortium (W3C)	Web Services Description Language (WSDL)
Internet Engineering Task Force (IETF)	Loose collection of organisations with internet standards as the main point of interest. For example, Light weight Directory Access Protocol (LDAP)
The Open Group	Sponsors sub groups, for example, Directory Interoperability Forum (DIF), Security Forum (SF)
International Organization for Standardization (ISO)	Well known international standards network. For example, International Telecommunication Union-Telecommunication Standardization Sector (ITU-T)

- **Liberty Alliance Project:** An organisation working mainly towards a solution/standard, they focus on the single sign on concept combined with federated identity.
- **Microsoft .NET Passport:** Primarily an organisational solution rather than standard. This provides a Microsoft managed authentication service for other web services/corporations.

Workflow
Workflow standards include:

- **Business Process Execution Language (BPEL):** Allows business processes (tasks) to be described by a combination of Web services and internal message exchanges.

Provisioning
Provisioning standards are hinted at from workflow standards (which ensure a process is followed by provisioning), but are otherwise not well covered, with one exception:

- **Service Provisioning Markup Language (SPML) (OASIS)**

IdM IN NG WIRELESS NETWORKS

Motivation

IdM issues were not critical in traditional telecommunication networks, because networks, applications, and billing for different services were not integrated. For example, if a service provider offers telephone, Internet access, and cable TV then all of these services are treated separately. Each service has its own subscriber database containing subscriber records and identity information.

IdM, in both concept and practice, has provided an effective alternative and complements to the existing security measures in enterprise networks. The NG wireless networks can be seen as a collective of organisations in addition to their customers. Considering its integrated nature, an IdM framework for NG wireless networks brings organisations closer than in the current telecommunications environment.

IdM in NG wireless networks will be more complex than enterprise and Web service solutions. It involves consolidation, management and exchange of identity information of users to ensure the users have fast, reliable, and secure access to distributed network resources across multiple service providers. Furthermore, NG wireless networks have to provide seamless and ubiquitous support to various services in a heterogeneous environment.

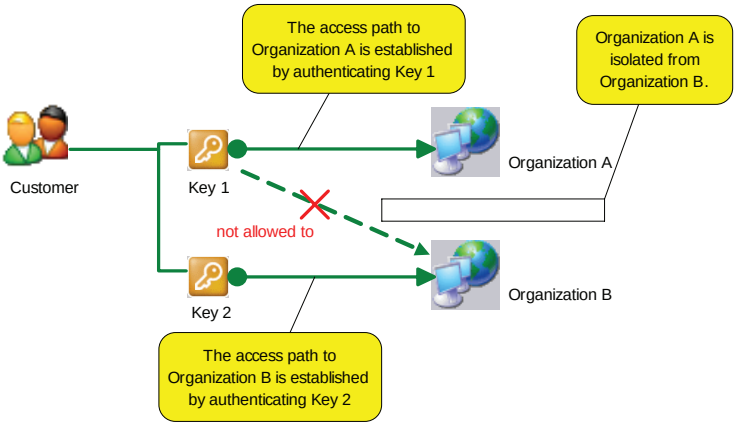
Carefully planned and deployed, IdM solutions in NG wireless networks can prevent fraud, improve user experience, assist in the rapid deployment of new services, and provide better privacy and national security. Conversely if it is not well planned and deployed, it can lead to identity theft, fraud, lack of privacy, and risk national security. In Australia, the cost of identity theft alone was estimated to be around $1.1 billion during 2001-2002 according to some 2003 SIRCA Research.

The digital identity information in NG wireless networks will be more complex because it has to cater to a number of mobility scenarios, access networks, and services. User identity could include a combination of names, unique user identifiers, terminal identifiers, addresses, user credentials, SLA parameters, personal profiles, and so forth. The digital identity information has to be exchanged between various entities in the networks for the purpose of authentication, authorisation, personalised online configuration, access control, accountability, and so forth. IdM in NG wireless networks is expected to provide a mechanism for controlling multiple robust identities in an electronic world, which is a crucial issue in developing the next generation of distributed services (Buell & Sandhu, 2003).

Let us have a look at a typical access scenario in traditional networks (shown in Figure 1). In these networks, one organisation is often isolated from another since each organisation is running and providing its services independently. Each customer has a number of identity credentials and each credential can only be used to access services from one subscribed organisation.

An expected access scenario in NG wireless networks is illustrated as Figure 2. The NG wire-

Figure 1. Typical access scenario in tradition networks



less network subscriber is expected to use the same credential to access multiple organisations. Without a well designed IdM solution, it will not be possible to cater to the following: (1) accessing the subscribed organisations frequently, (2) increased frequency of handoff between multiple organisations in NG wireless networks, and (3) mutual authentication between subscriber and service provider, or between various service providers. A security breach on any component of the NG wireless networks will result in more severe consequences for all the other business partners. Therefore, in order to maintain a similar level of trust, reliability and profitability for the NG wireless networks, integrated IdM measures in NG wireless networks must be taken.

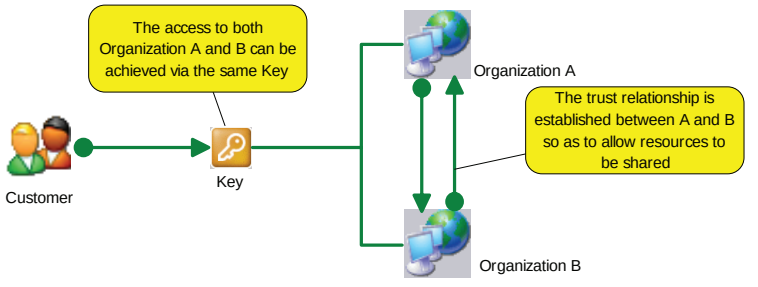
Benefits in NG Wireless Networks

A carefully researched IdM framework for NG wireless networks has a number of benefits for NG wireless networks users, operators, and service providers.

1. User experience is often improved as users can ubiquitously access services and applications of their choice over a number of service providers without going through separate logins and avoiding the need to remember multiple usernames and passwords or use multiple tokens.
2. Service delivery can be improved, for example, the time required to get new subscriber access is reduced.
3. It supports flexible user requirements and personalisation.
4. As with enterprise networks, there are numerous benefits such as reduction in the cost of new service launch, operation and maintenance (O&M) and increased return on investment (ROI) for NG wireless network operators and service providers.
5. IdM is expected to support distributed network architectures where entities communicate through open but secure interfaces.
6. It is necessary for seamless user mobility across networks and terminals.
7. A carefully researched and implemented IdM solution improves the security of the NG wireless networks and the user confidence in the use of the services.
8. IdM will assist in the efficient implementation of current and new legal and compliance initiatives about user data, behaviour and privacy.
9. IdM is expected to support number and service portability of users in an NG wireless network environment.

However, introducing an IdM solution can bring new forms of security issues and threats. As you

Figure 2. Simple access scenarios in NG wireless networks



consolidate the identity-related information, you create a new target for security attacks. But the advantage of implementing IdM is that you do not have to worry about protecting disparate solutions. Now you are able to consolidate your defences to one point.

Requirements for IdM in NG Wireless Networks

In this section, an analysis of the requirements for IdM in NG wireless networks is presented. The analysis will be undertaken from three perspectives: user, network, and service. The requirement analysis is expected to cater to the needs of end users, network operators, and service providers in terms of some of NG wireless networks' key functional classifications such as operation, mobility, security, personalisation, and so forth.

Before we get started, a definition of various terms used in NG wireless networks is given:

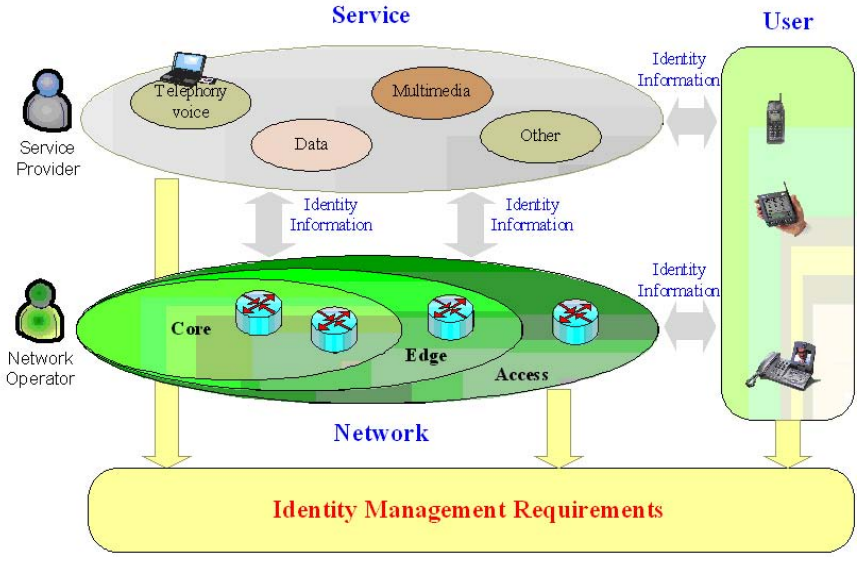
- **User:** A user refers to a person or entity with authorised access (The Health Insurance Portability and Accountability Act (HIPAA), 2005). In describing NG wireless networks, the term *end user* is often used to refer to a person or entity that uses network resources or services.
- **User terminal:** The user terminal is the device that is used by an end user to access the services provided by the NG wireless networks. It can be a mobile station (MS) or a laptop.
- **Network operator:** Network operator is defined as a legal entity that operates, deploys, and maintains network infrastructure. In NG wireless networks, the networks provided by network operator become the intermediary broker between services and subscribers.
- **Service:** Besides the traditional legacy services, like telephony voice and data, the NG wireless networks can also offer new value-added services to accommodate increasing multimedia demands, for example, video conferencing.
- **Service provider:** The services in NG wireless networks can be provided by different service providers using a single network platform or separate network platforms offered by a network operator.

End User Requirements

Unique Identity for User and Terminal

A unique universal identity will have to be assigned to each individual user of the NG wireless networks and to each user terminal that a user may use to access services of the NG wireless networks. Examples of such identity in Global System for Mobile Communications (GSM)/Universal Mobile Telecommunications System (UMTS) networks include the International Mobile Subscriber Identity (IMSI) and International Mobile Equipment Identity (IMEI). Users should have a single identity regardless of the access technology or network being used.

Figure 3. An overview of IdM requirements and NG wireless networks



The user identity must possess sufficient features that enable it to be used in a variety of end user terminals (computer, mobile phone, landline phone). Additionally, the unique identity may be required to be compatible across several IdM systems.

Storage of User Information

User identity information may be stored in many locations: user card, home network, visited network, service providers, and so forth. Sometimes, the stored user information can be used as a credential for fast authentication, for example, HTTP cookies are adopted to facilitate quick access to protected Web sites. However, such kind of convenience can have a security risk as the security at user end is more likely to be compromised. NG wireless networks designers have to carefully decide how much information needs to be securely stored at user end. Any identity-related information stored at the user end has to be secure.

Exchange of User Identity

The unique identity allocated to a user should be treated confidentially. Sometimes, it is a risk to transmit the real identity of a user through radio or other public transmission mediums, like the Internet, or exchange it directly with unauthorised parties. Special measures must be taken to ensure that user identity is not disclosed during the exchanging process. One possibility to overcome this problem is to use a temporary user identity that is derived from the unique user identity and is valid for a fixed period of time. Once the validity of the temporary identifier is expired, a new temporary identity is generated. This way the real identity of a user is never compromised.

Self-Service

Self-service is the ability of a user to actively manage part of his or her records without requiring the intervention of help desk or support staff (Reed, 2002). This is an important requirement in all IdM systems. All NG wireless networks users should be able to securely manage some of their own identity information such as changing passwords, subscription status, choosing their mobility status, changing roaming authorisation, modifying user profiles, enabling location based services, and so forth. Users should also be able to modify content

filtering options for upstream and downstream traffic.

Users should be able to view their up-to-date billing records and service usage patterns. To increase trust, users should be able to view their self-service activity journal, which displays all the self-service activities performed by a user.

An IdM system should be able to cater to situations where a user wants to delegate self-service privileges to another user such as maintaining accounts of family members.

Single Sign-On

An important user requirement of NG wireless networks is single sign-on. This means that once a user is authenticated, the user should have access to the entirety of their subscribed services without having to repeat the authentication process for each subscribed service.

Security and Privacy

To increase security, users should be able to choose end-to-end data encryption. Unauthorised users should not be allowed to access, view, or modify identity information.

With the growing awareness of privacy and the wish to protect it, users would be looking for more control over their privacy, in particular, what information is known about them and by whom. With an effective IdM system, a user should be able to exert some control as to how much identity data they want to release (which may consist of approval for sending some particular identity attributes) as well as being able to retrieve data concerning the location of their identity data and who is able to currently access it.

Users should also be able to stay anonymous while accessing some network services such as network time protocol (NTP).

Access Network Selection

NG wireless networks users should be able to choose between access networks based on a number of factors such as bandwidth, quality of services, cost, location, and so forth. The user should be able to move between the different access technologies with minimum configuration change and get access consistently to their services according to their user profiles.

Mobility

Mobility across heterogeneous environments requires service adaptation for terminal mobility as well as personal mobility (France Telecom, 2002). In the event of service difficulty during mobility, users should receive user friendly notification with choices of actions to restore the service without the need to contact support staff.

Another related implication is that a user, who is changing access networks during a session, should be able to continue to access the same service without repeated authentication. For example, a mobile user should be continuously attached to a network when there is a handover from a UMTS network to a wireless LAN (WLAN).

Network Operator Requirements

In the NG wireless networks, network operator will be responsible for maintaining and managing network infrastructure. In the ITU's general reference model for NG networks (ITU-T, 2004), network operator will be responsible for taking care of management plane, control plane, and user plane in the transport layer.

Interface to Other Network Operators

Because of the mobility of users, it is difficult for a single network operator to cover a vast geographical area. Thus national and global roaming among multiple network operators is needed in NG wireless networks. In order to support roaming between NG wireless networks, identities of users and networks need to be authenticated before access to resources is granted through a visited network. It may be cost effective for a roaming user to access services in the visited network than in the home network. A network operator should give choices to roaming users on the selection of services.

Interface to Trusted Third Party

It is possible that all of the IdM is performed by a third party that is different from the network operator or service provider. This third party will issue, authenticate, and control NG wireless networks user identities. A secure interface has to be provided between the NG wireless networks and the trusted third party.

Identity Requirements

The NG wireless networks operator should be able to maintain a unique identity for each user, terminal, network element, location area, and so forth, regardless of service and technologies used.

If the user is using faulty or dubious terminal equipment, it should be possible to bar services to the user.

The digital identity stored in a network should cater to various types of user identity information and data structures.

As in enterprise networks, proper implementation of account lifecycle management is required, that is, administrators should be able to manage the state of a user account for the complete span of that account. Even if an account is deleted or disabled, an audit history of the account should be maintained.

If necessary, the network operator should be able to remove self-service privilege of some users.

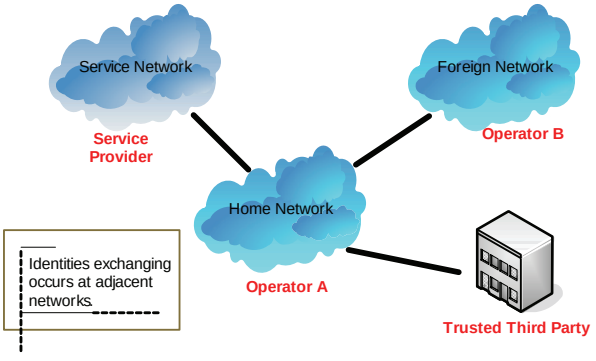
The IdM system should support open standards in order to interact with multi-vendor terminals and network elements. It should be compatible with existing legacy systems and be able to adapt to emerging technologies, methods, and procedures.

Scalability and Performance

The IdM system should be able to store, retrieve, and exchange billions of identity information in a highly seamless, scalable, quick, and efficient manner to facilitate multiple real-time service requests from users.

It should achieve a high level of availability by incorporating fault-tolerant redundant system implementation. Furthermore, it should implement

Figure 4. Network operator's position in the NG wireless networks



geographically distributed IdM servers in order to increase performance efficiency by load sharing and providing high availability. It should also maintain integrity and consistency of identity data across distributed identity information stores.

Mobility Management

NG wireless networks should be able to cater to the mobility requirements of users. This could include personal and/or terminal mobility, roaming, or nomadism. Mobility management may require a combination of identification, authentication, access control, location management, IP address allocation and management, user environment management, and user profile management functions. The network should cater for both foreign network IP address and home network IP address allocation scheme.

Security

Security requirements for NG wireless network operators should cover privacy, confidentiality, integrity, authenticity, non-repudiation, availability, intrusion detection, and maintenance of audit records as described later on.

Users and terminals should be reliably authenticated by the network operator using a nominated set of authentication credentials such as passwords, smart cards, biometrics, and other industry standard

methods. All the identity data should be kept in a very secure and scalable manner. Unauthorised access to identity data should be prevented.

Intrusion detection is required to detect and prevent security breaches with the network operator. This can also be done to minimise the fraudulent use of resources in a network.

Network administrators should be granted different levels of access according to their authority within the organisation. For accountability and security reasons, consistent and reliable audit records of administrative activities must be kept.

In order to apply user and data security such as confidentiality, integrity, and authenticity, the IdM system should securely store and exchange relevant encryption keys.

Billing

Up-to-date, accurate, and detailed billing information should be maintained by the network operator. When there is more than one source sending billing data, the network operator has to consolidate this information from various sources.

Furthermore, when a subscriber is roaming in a foreign network, charging records from that foreign network has to be authenticated to prevent fraudulent usage of services.

The network operator should be able to support a number of charging mechanisms such as charging based on usage, access networks, time, geographical area, and so forth. All of these different charging mechanisms should be compatible with the IdM system.

Service Provider Requirements

A user may require services from a number of service providers. In this scenario, the home operator and the service provider(s) should support secure access and exchange of user identity and billing information.

The identity of each user should be uniquely and reliably identified by a service provider. The service providers may have to rely on third party IdM providers where the user has already established an account.

The IdM and related systems should support open standards with choices of number of technologies in order to interoperate with other entities.

Interface to Other Service Providers

Users may subscribe to the services offered by different service providers. Thus, the interoperability among service providers is important. User identity information may be exchanged between a group of service providers in order to improve "transparent user experience." This also requires trust to be established between these service providers.

Interface to Network Operator

A well-defined, open interface needs to be provided to the network operator at the service provider end. This would give service provider the necessary authentication, authorization and accounting (AAA) to access network resources offered by network operator.

Interface to Trusted Third Party

An interface to trusted third party would give service provider an opportunity to use external AAA services. By doing so, the complexity of implementation of services would be reduced. The authentication of users can be centralised.

Mobility Management

Some services require information about the current location and connectivity of subscribers. These are referred to as location-dependent or location-aware services. To provide such services to end users, a service provider must be able to access mobility-management-related information maintained by network operators. Subscribers have to consent to the release of this sensitive private information to service providers. Furthermore, when there are updates to location or mobility management data in the network operator, the update have to be passed to the subscriber.

Security

As one of the main holders of identity data about subscribers, service provider would have to exercise extra vigilance in ensuring that the data that they store is kept secure.

Additionally, in order to ensure a high degree of mobility and choice to the end user, this identity information must be able to be easily and securely transferred between different service providers depending on the end user's current choice.

Billing

A number of requirements pertaining to billing for network operators are equally applicable to service providers. Billing records of the user should be dynamically generated according to the usage.

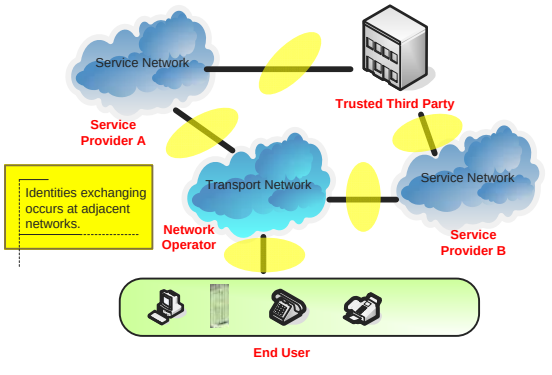
Regulatory Requirements

It is expected that the NG wireless networks should support open standards and choices among a number of technologies to promote competition and flexibility. Thus, any IdM solution that favours a particular standard or technology can be deemed anti-competitive.

Privacy is an important issue that has to be addressed directly by IdM products and solutions. There are increasing concerns about the fact that enterprises, e-commerce sites, governments, and third parties can access and correlate people's identity information, sell this information, or misuse it. Current laws and legislation only partially address this problem. Despite the fact that many efforts have been made at the legislation level, there are still a lot of problems that have to be addressed. Furthermore, privacy laws can differ quite substantially depending on national and geographical aspects. All of the regulatory requirements pertaining to privacy and confidentiality of subscribers' personal information should be built into the IdM solution in NG wireless networks.

Identity subjects have little control over the management of their identity information. It is very hard (if not impossible) for the subjects of identity information to define their own privacy policies (or delegate this task to trusted third parties), check for their enforcement, track in real-time the dissemination and usage of their personal information be alerted when there are attempts to use or misuse it, and so forth. Because of emerging data protection laws, new legislation and the need of service providers to simplify the overall management, there is a tendency towards the delegation to users of the authoring of their identity profiles.

Figure 5. Service provider's position in the NG wireless networks



Legal Requirements

Privacy and confidentiality of subscribers' personal information and prevention of unauthorised access should be maintained at all times by network operators and service providers and any third party organisations involved in the NG wireless networks space.

If information has to be shared, subscribers should have a choice of the types of subscriber information that can be shared with various third parties. Reliable audit records of administrative and user activity should be kept, which could be retrieved and submitted to courts and other entities to meet legal requirements.

Legal interception of subscriber data should be possible. One of the new requirements for telecommunication network operators is to collect and pass on real-time transactions of target subscribers to law enforcement authorities (Council of Europe,

2001). Legal interception of subscriber data should be possible whichever network or service a subscriber is using.

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KEY TERMS

Access Control: Access control is used to determine what a user can or cannot do in a particular context.

Auditing and Reporting: Auditing and reporting involves the creation and keeping of records, whether for business reasons (e.g., customer transactions), but also for providing a "trail" in the event that the system is compromised or found faulty.

Authentication: Authentication is the process by which an entity provides its identity to another party, for example, by showing photo ID to a bank teller or entering a password on a computer system.

Authorization: Authorisation is the process of granting access to a service or information based on a user's role in an organisation.

Context: Context can refer to the type of transaction or organisation that the entity is identifying itself as well as the manner that the transaction is made.

Digital Identity: Digital identity is the means that an entity can use to identify themselves in a digital world (i.e., data that can be transferred digitally, over a network, file, etc.).

Identity: The identity of an individual is the set of information known about that person.

Network Operator: Network operator is defined as a legal entity that operates, deploys, and maintains network infrastructure.

Profile: A profile consists of data needed to provide services to users once their identity has been verified.

User: A user refers to a person or entity with authorised access.

User Terminal: The user terminal is the device that is used by an end user to access the services provided by the NG wireless networks.

Chapter V
Wireless Wardriving

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ABSTRACT

Wardriving is the practice of searching wireless networks while moving. Originally, it was explicitly referred to as people searching for wireless signals by driving in vans, but nowadays it generally identifies people searching for wireless accesses while moving. Despite the legal aspects, this "quest for connectivity" spawned a quite productive underground community, which developed powerful tools, relying on cheap and standard hardware. The knowledge of these tools and techniques has many useful aspects. Firstly, when designing the security framework of a wireless LAN (WLAN), the knowledge of the vulnerabilities exploited at the basis of wardriving is a mandatory step, both to avoid penetration issues and to detect whether attacks are ongoing. Secondly, hardware and software developers can design better devices by avoiding common mistakes and using an effective suite for conducting security tests. Lastly, people who are interested in gaining a deeper understanding of wireless standards can conduct experiments by simply downloading software running on cost effective hardware. With such preamble, in this chapter we will analyze the theory, the techniques, and the tools commonly used for wardriving IEEE 802.11-based wireless networks.

THE (ART OF) WARDRIVING

Owing to the absence of physicals barriers, the wireless medium, and consequently wireless (WLANs) are accessible in a seamless manner. Thus, checking for the presence of some kind of wireless connectivity is quite a natural instinct; it is sufficient to enable the wireless interface and wait. This action is a very basic form of wardriving, a term originally coined by Shipley (2000) to refer to the activity of "driving around, looking for wireless networks." This activity rapidly evolved, and nowadays it implies three basic steps: (1) finding a WLAN, (2) defining precisely its geographical coordinates by using GPS devices, and (3) publishing the location in specialized Web sites to enrich the wardriving community.

With the increasing diffusion of WLANs, especially those based on the cost effective IEEE 802.11 technologies, searching for wireless signals is a quite amusing and cheap activity. However, the IEEE 802.11 family originally relied (and still relies) on weak security mechanisms. In addition, many users unconsciously operate their wireless

networks without activating any confidentiality, integrity, and availability (CIA) mechanisms: opportunity makes the thief. Then, wardriving becomes a less noble hobby, since many wardrivers try also to gain access to the discovered networks; many of them are only interested in cracking the network, while a portion will steal someone else's bandwidth. In this perspective, another basic step has been introduced: (4) trying to gain access to the WLAN.

It is also interesting that wardriving is becoming part of the urban culture. For instance, it spawned a strange fashion called *warchalking*, that is, *the drawing of symbols in public places to advertise wireless networks*, as defined by Matt Jones (as cited in Pollard, 2000).

Then, why is it important to know about wardriving?

Firstly, because you must become conscious that an active WLAN can trigger "recreational activities," even if it is solely employed to share a printer. Secondly, the coordinated effort of many people highlighted several security flaws in the IEEE 802.11 standards and produced effective tools to test (well, actually, to compromise) the security of access points (APs). Thirdly, while performing their "raids," *wardrivers* discovered flaws in the devices; consequently, this is a valuable knowledge that could be used to avoid further errors. Lastly, trying to be a wardriver is an instructive activity that will help to better understand WLANs technologies, develop your own auditing tools and procedures, and prevent, or at least, recognize attacks.

HARDWARE AND SOFTWARE REQUIREMENTS

In the basic form of searching for a WLAN, the act of wardriving could be simply performed by having a device equipped with an IEEE 802.11 air interface. Then, one can use a standard laptop, a wireless-capable console, or a handheld device. However, the typical gear consists of a laptop and a GPS device (even if not strictly necessary). Nevertheless, many wardrivers do prefer a Personal Computer Memory Card International Association (PCMCIA) wireless card that is capable to connect with an external antenna to sense a wider area. With this basic setup you should be able to enable the wireless interface and start scanning the air. But, in order to conduct more sophisticated actions, a deeper understanding of aspects related to hardware and software should be gained. A detailed breakdown follows.

Wireless Interfaces

Each model of wireless interface differs in some way. Regardless of different power consumption, better antennas, and so on, two major aspects must be taken into account: the chipset and the availability of ad hoc drivers. The chipset roughly represents the soul of a wireless interface and it is mostly responsible of its capability. For instance, some chipsets do not allow assembling ad hoc frames, preventing from exploiting particular attacks. The reasons are different: the chipset could lack the logic to deal with raw packets or its specification is not known, discouraging tool developers to exploit such functionalities. At the time of this writing, cards based on the Prism chipset are the most studied and documented, resulting in a variety of pre-made tools for preparing packets.[1] Lastly, being the interfaces engineered for providing connectivity and not such kind of tasks, manufacturers often change the internal chipset, even if maintaining the model or the brand name. This is why not all wireless cards are the same, and you should check their specifications carefully if you plan to use them for wardriving.

Device Drivers and Scanning

Device drivers provide the basic bridge between the user software and the hardware. Having a flexible device driver is mandatory to reach the soul of your interface. The best device drivers for wardriving are available for the aforementioned chipset, and for Unix systems. In addition, owing to its open source nature, Linux has the best available drivers.

The importance of drivers becomes evident when you scan the air for a network. About the totality of the bundled drivers does not allow to perform the so called *passive scan*. Passive scan implies that your interface operates in *passive mode*, often called *radio frequency monitoring* (rfmon) mode. While you operate in rfmon, you can scan APs and remain undetectable, since your card does not send any probe packets.

Conversely, when acting in *active mode*, which is the standard configuration, as soon as you start looking for an AP, you will be revealed. The ability of switching from active to passive mode and vice versa is provided by the drivers. Many drivers do not provide this functionality, while others have this functionality hidden and must be reverse engineered.

For the most popular chipsets, alternative drivers that allow the user to put the card in rfmon are available. If you plan to do undercover works, you should check the driver availability.

However, the active mode is faster than the passive mode. While operating in passive mode, the average time needed for scanning a channel is about 50 ms. Obviously, multiple channels scan requires $n \bullet 50$ ms. Conversely, when performing scanning operations in active mode, the needed time is lower. In fact, the operations required are: transmitting a probe request + waiting for a DCF IFS interval + transmitting a probe response. The overall time needed per channel is roughly equal to 0.45 ms. Again, scanning *n* channels increases the needed time accordingly (Ferro, 2005).

An Example of Driver Hacking

As said, the ability of enabling an air interface in rfmon could be available in the driver, but not documented. This is the case of the driver for the AirPort Extreme wireless adapters bundled with MacOS X. This example is introduced for didactical purposes, stressing how a simple "hack" can transform a partially closed platform in an excellent wardriving configuration.

In a nutshell, OSX drivers are implemented via *kernel extensions* (kexts) that are similar to Linux's modules. Every kext is bundled with a kind of configuration file called *Info.plist*. The *Info.plist* is a XML file containing a dictionary that describes the properties of the belonging kext. The "hack" consists in a simple operation (i.e., changing a string) but it took time to discover.

Firstly, the proper *Info.plist* must be located. In a console type:

```
Mud:Luca$ cd /System/Library/Extensions/AppleAirPort2.
kext/Contents/
```

Hence, you can see the content of the *kext* upon simply typing:

```
Mud:Luca$ ls
Info.plist          MacOS          version.plist
```

Then, it is possible to modify the *Info.plist*

```
Mud:Luca$ vim Info.plist
```

The key responsible of enabling the *rfmon* follows, in boldface:

```
<key>IOKitPersonalities</key>
    <dict>
        <key>Broadcom PCI</key>
        <dict>
            <key>APMonitorMode</key>
            <false/>
```

Switching the dictionary entry **<false/>** to **<true/>** enables the AirPort Extreme card in rfmon.

However, such a task could be performed programmatically.

This is the approach taken in KisMAC, which is popular among wardrivers. As an example, in the following, the Objective-C code snippet checking whether or not the wireless interface is rfmon is depicted in Snippet 1.

Roughly, the steps presented in Snippet 1 allow the user to: (1) obtain a handler to the proper *Info.plist* file; (2) prepare a dictionary for parsing the *Info.plist*; and (3) check if the **<APMonitorMode>** key is **<false/>** or **<true/>**.

The Operating System and Other Matters

Needles to say, the operating system (OS) plays a role. For instance, when processing data for

Snippet 1. How to programmatically retrieve if an AirPort card is configured in rfmon

```
fileData = [NSData dataWithContentsOfFile:
@"/System/Library/Extensions/AppleAirPort2.kext/Contents/Info.plist"];          1

dict = [NSPropertyListSerialization propertyListFromData:fileData
mutabilityOption:kCFPropertyListImmutable format:NULL errorDescription    :Nil]; 2

if ([[dict valueForKeyPath:@"IOKitPersonalities.BroadcomPCI.APMonitorMode"]
boolValue]) return YES;                                                         3
```

bruteforcing an encrypted flow, a good symmetric multi process (SMP) support is a must (as well as a good multi-threaded implementation).

In addition, many APs can reject data from unrecognized MAC addresses: for this reason, having an OS that allows the user to change the MAC address of active interfaces is important. Lastly, many tools only run on *nix operating system. However, the traffic collection phase could be decoupled by the processing, hence allowing the user to collect data on a machine and process it on another. As a consequence, simple devices (e.g., with low computational power) could be employed to collect data and discover APs (e.g., PDAs and portable gaming devices), while a standard PC could be used for processing the collected traffic.

XOR Arithmetic and CRC32 in a Nutshell

In order to understand the security mechanisms, and possible attacks, a little remark about eXclusive OR (XOR) arithmetic and the properties of CRC_{32} functions, employed for data checking, are presented. Basically, the XOR operator respects the properties presented in Table 1.

Table 1. Basic XOR arithmetic ($\oplus$ represents the XOR operator)

Operation	Result
$0 \oplus 0$	0
$1 \oplus 0$	1
$1 \oplus 1$	0
$(A \oplus B) \oplus A$	B
$(A \oplus B) \oplus B$	A

Concerning the CRC_{32}, it is employed to check data and to assure integrity. It has not the cryptographic strength of other hashing algorithms, such as the MD5 and the SHA1 (Schneier, 1996). The CRC_{32} employed in the wired equivalent privacy (WEP) algorithm has two major properties, as presented in Table 2.

ABOUT THE SECURITY OF IEEE 802.11

The IEEE 802.11 security framework has changed during the years: from the flawed WEP, to the wireless protected access (WPA) introduced by the Wi-Fi alliance in late 2002. However, since mid-2004, the IEEE 802.11i Working Group (WG) introduced a framework based on the 802.1X and the extensible authentication protocol (EAP), to bring the wireless security to the next level; such effort is known as WPA2.

Even if highly criticized, the security mechanisms proposed by different WGs have developed having in mind different operative contexts. For instance, the WEP (as the name suggests) has been developed to prevent simple connection attempts, while WPA has been developed to offer an adequate resistance to well-planned attacks. Currently, an average wardriver can: surely connect to an unprotected AP, spend 10 minutes to 1 hour to break the WEP, and crack a WPA-protected AP in some of its weak variants and well-suited circumstances. In order to understand the common technique employed by wardrivers, the commonly adopted security countermeasure will be briefly explained.

Table 2. Properties of the CRC_{32} function employed in the WEP

Property	Application
Linearity	$CRC_{32}(A \oplus B) = CRC_{32}(A) \oplus CRC_{32}(B)$
Independence of WEP Key	It is possible to flip bits without being recognized by the WEP

No Encryption

Many wireless networks operate without any encryption, and "security" is delegated to other mechanisms. It must be underlined that the lack of encryption allows everyone to listen to the channel and analyze the traffic (that flows in clear form if no security mechanisms at higher layers are adopted). Hence, for these users, "security" is solely a synonym of "preventing" the unauthorized usage. The most adopted methods are: MAC address filtering and hiding the service set identifier (SSID). They will be briefly explained, highlighting why they cannot be perceived as secure countermeasures.

MAC Address Filtering

MAC address filtering is a basic technique implemented in about the totality of the commercially available APs. Basically, before authorizing an association, the AP checks the allowed MAC addresses in a white list. The rationale under the approach relies on the uniqueness of the MAC address. As a matter of fact, this technique only discourages the occasional wardriver, but it is quite useless. In addition, it could be used jointly with WEP or WPA, in order to have another barrier if an attacker cracks the encryption mechanism. However, frame headers are never encrypted; hence, it is a simple task to retrieve some valid MAC addresses (e.g., by simply monitoring a channel). Then, there are a variety of tools for changing the MAC address of a wireless interface, performing the so-called MAC-spoofing.

Hiding the SSID

In order to advertise a network, it is possible to broadcast a special identifier called SSID. The standard allows the user to embed the SSID within beacons sent by APs or wireless routers. In order to "join" a WLAN, you must know its SSID. As a consequence, many users/administrators disable the SSID broadcasting, to prevent unauthorized accesses. However, this measure only prevents a minority of attempts. In fact, there are several tools and techniques that allow a user to uncloak a hidden SSID. A thorough discussion about such tools will be presented in the following sections, but we outline the basic procedures here. Specifically, it is possible to: (1) recover information about SSID contained in frames sent by other stations in the network; for instance, the SSID is contained in association request packets; and (2) if such frames are not available, it is possible to spoof the IEEE 802.11 de-authentication frames of target clients. This causes a client to start a new authentication and association round with the AP, providing the needed frames.

WEP Encryption

The scientific literature, as well as daily practice, commonly suggest that the WEP is a highly insecure encryption mechanism. No matter about the skill of the wardriver, or the quality of the implementation in the AP: a WEP-secured network can be cracked in a period varying from 5 minutes to 1 hour. Moreover, many tools implement automated procedures; thus, cracking the WEP is as simple as pressing a keyboard shortcut.

Understanding the Effective Strength of the WEP

Often, marketing collides with engineering: this is the case of the WEP. In order to understand the effective strength of the WEP, as well as its weak

Figure 1. The message in clear form to be encrypted with WEP

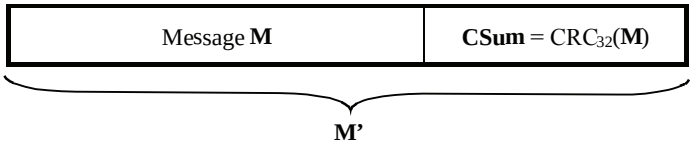
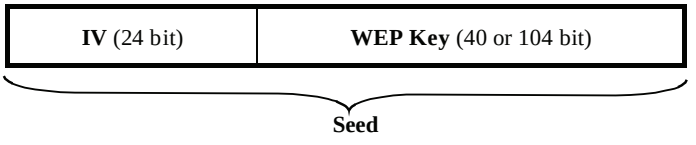


Figure 2. The seed used to encrypt packets with WEP



points, let us summarize its basic functionalities. The WEP performs the encryption per packet; let a given packet **M** represent a message in clear form to be sent. Hence, the following steps happen:

A 32-bit cyclic redundancy check (CRC) algorithm is applied to **M** in order to produce a checksum. Then: **CSum** = CRC_{32}(**M**). Basically, a CRC is introduced to assure message integrity. However, the use of CRC-like codes in this kind of environment has been proven to be very dangerous.

Let us define as **M'** the message actually processed by the WEP algorithm, hence to be really sent over the channel. **M'** is depicted in Figure 1.

Then **M'** is encrypted by using the RC4 algorithm, that relies on a stream cipher approach. Thus, the actual **Seed** used by the WEP is the combination of a 24-bit initialization vector (IV) and the WEP key, as depicted in Figure 2.

Referring to Figure 2, two different WEP keys are available: 40-bit long keys adopted in the *standard implementation*, or 104-bit long keys adopted in the *extended implementation*, which has been introduced to prevent brute force attacks. Here comes the marketing: a *"64 bit WEP secured network" actually relies only on 40-bit long keys*, since 24-bits represent the IVs. For the same reason, a *"128-bit WEP secured network" only relies on 104-bit keys.*

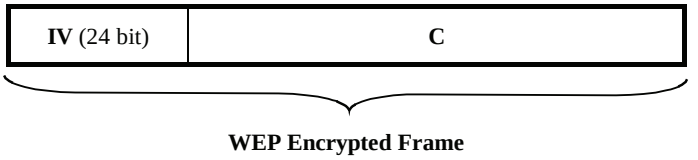
Splitting the **Seed** in two sub parts (the **IV** and the **WEP key**) is one of the major flaws of the procedure. However, the reason is rooted both in the nature of the RC4 and wireless channels. The RC4 has been used in the WEP since it is widely adopted and well studied. But its application over wireless channels poses some drawbacks. In fact, wireless channels frequently drop packets, thus maintaining a proper synchronization in the stream to allow the decryption operations is a challenging task. Consequently, to overcome the possibility of packet loss and stream de-syncing, each encrypted packet is sent along with the **IV** that generates its keystream. This represents another weakness in the algorithm, since it allows a wardriver (attacker) to seamlessly collect IVs.

Concluding, the ciphered text **C** is provided by:

$$\mathbf{C} = \mathbf{M'} \oplus \mathbf{RC4}_{\mathbf{Key}}$$

where, $\oplus$ represents the XOR operator, and $\mathbf{RC4}_{\mathbf{Key}}$ is the keystream generated by the RC4 algorithm by feeding it with **Seed**. Figure 3 depicts a WEP-encrypted packet that could be collected and exploited by a wardriver. Needles to say, IVs convey precious information, and in the following, we show how standard tools can exploit this.

Figure 3. A WEP encrypted frame. Notice that the IV is sent as cleartext.



WPA Encryption

As previously explained, WPA encryption schemes have been introduced to overcome the drawbacks in the WEP. The WPA exists in two different flavors: 802.1x jointly used with the temporal key integrity protocol (TKIP) that is intended for enterprises, and the less secure pre-shared key (PSK), possibly jointly used with the aforementioned TKIP. The 802.1x + TKIP is a quite secure protocol, and difficult to crack by *wardrivers*, but the PSK version still has some flaws. The WPA has been proved to be quite secure; thus, we will omit its details in this chapter.

Some Considerations about Layer 1 Security

All the aforementioned encryption mechanisms have been introduced to cope with the simplicity of sensing a WLAN, and consequently, to collect data. Then, it is hard to implement OSI-L1 security mechanisms, as it can be possible in wired networks. However, a basic countermeasure could be exploited: adjusting the wireless power. Conversely, wardrivers can adopt high gain antennas to intercept distant APs. Those concepts will be further discussed.

Wireless Power

Many APs allow changing the power employed for transmitting data. However, many users keep the default values or use more power than required. Despite the waste of energy, this raises also some security risks. For instance, if there is the need of covering a conference room, it is harmful to irradiate more than required power, resulting in the chance of detecting (and using) the WLAN also from the outdoor. This is at the basis of wardriving. In fact, wardrivers will seldom enter private areas; rather, they will station in streets and public places, capitalizing the unsolicited wireless coverage. Then, as a rule of thumb for protection, it could be useful to irradiate only the required power: no more, no less.

Antenna Gain

As said, wardrivers often utilize high gain antennas to reach distant networks. Thus, reducing the transmission power of the APs might not be enough.

Commonly, there are several techniques to replace the standard antenna available at the network interface, but they are out of the scope of this work. The simplest technique is to use an external PCMCIA wireless card equipped with a connector for an external antenna. One of the most interesting accessories is the *pigtail*. The pigtail is a converter allowing the user to connect high gain antennas with a wireless card, even if the terminal connectors are different (e.g., wireless cards often have MC-Card, MMCX or RP-MMCX connectors).

WEP ATTACKS

As discussed in the *Understanding the effective strength of the WEP* section, WEP offers different alternatives to be attacked and cracked. In this section, we will introduce the most popular attacks, and then we will present some practical examples. Besides, attacks could be roughly grouped in two

categories: passive and active. A passive attack solely relies on the traffic collected, while an active attack consists also in injecting some additional traffic in the network. For instance, active attacks are employed to stimulate the traffic to collect if there are not any clients connected to an AP at a given time. The latter techniques will be presented when needed, then in the *Example* section.

Bruteforce Attacks

Every security algorithm is exposed to bruteforce attacks. The key point is if a bruteforce attack is feasible. As said, WEP exists in two variants. Concerning the 40 bit standard implementation, a bruteforce attack could be feasible. Probably, an occasional attacker will have a machine allowing to check 10,000 to 15,000 keys/second; hence, it is not sure that he/she will complete the attack (on an average laptop, 200 days are required). But an organization or a professional attacker can try to successfully bruteforce the WEP in the 40-bit variant. Nevertheless, nowadays there are several software libraries for parallelizing computations, as well as software tools for building clusters (e.g., Beowulf or Mosix for the Linux platform and XGrid for MacOS X). Owing to the availability of the source code of bruteforcing tools, porting them on such frameworks could be possible. Actually, bruteforce is never employed, since it is possible to successfully crack the WEP in simpler and quicker ways.

Conversely, the 104-bit long key available in the WEP extended implementation is immune against bruteforce attacks (with a standard gear, about 10^{19} years are needed).

The Tim Newsham's 21-Bit Attack

Tim Newsham is a well-known security expert and consultant. Among wardrivers he is very popular for inventing the 21-bit attack (Newsham, 2003), allowing to bruteforce some WEP implementations in minutes.

Basically, Newsham noticed that several vendors generate WEP keys from text, in order to make easy-to-use products and cover a wider market range. Usually, the user must insert a *pass phrase*, something like: "*Ken sent me*" and the wizard will automatically generate a WEP key. However, many generators appear to be flawed. He discovered that two steps in the generation process reduce the "strength" of the key; specifically:

1. The ASCII mapping reduces the entropy: usually ASCII strings are mapped to 32 bit value and the XOR operation guarantees four zero bits. In addition, the highest order bit of each character is equal to zero. Then, only seeds from 00:00:00:00 e 7f:7f:7f:7f can occur.
2. The use of Pseudo Random Number Generation (PNRG) reduces the entropy: for each 32bit output, only a portion of the available binary word is considered (e.g., bits 16 through 23). Besides, the generator has the properties of generating bits with different degrees of "randomness." For instance, a bit in position k has a cycle length of 2^k. Then, Newsham noticed that the produced bytes have a cycle length of 2^{24}, thus reflecting in seeds ranging from 00:00:00:00 and ff:ff:ff:ff.

In order to discover the key, it is sufficient to consider seeds ranging from 00:00:00:00 through 00:7f:7f:7f with zero highest order bits, hence reducing the space and only analyzing 2^{21} words. As a consequence, it is possible to bruteforce such flawed implementations in minutes. The most popular implementation of Newsham's 21-bit attack is available in the KisMAC tool. According to KisMAC documentation, Linksys and D-link devices appear, at the moment, the most vulnerable to this attack.

Weak IVs

This attack relies on how the RC4 is used to produce a WEP-encrypted stream. Basically, some IVs can reveal some information about the secret key embedded in the first byte of the keystream. Then it is enough to collect a sufficient number of weak IVs and, if the first byte of the keystream is known, it is possible to retrieve the key.

Regarding the collection of the first byte of the keystream, the IEEE 802 standard gives some useful hints. In fact, IEEE 802.11 frames always begin with the SNAP field, which most of the time is set to 0xAA. Then it is sufficient to collect weak IVs that come in the form of:

(Y+3, 256, X)

where Y is the portion of the key under attack, the second value is 256, since RC4 works on a modulo-256 arithmetic, and X can be any value. Fluhrer, Martin, and Shamir (FMS) have developed an efficient attack available in different tools. However, the core of the attack is out of the scope of this chapter.

As a concluding remark, new devices tend to avoid weak IVs' generation. In fact, hardware developers better engineer their devices, increasing attention to the IVs' generation mechanism.

Keystream Reuse

Suppose to be in the following scenario: two different cleartext messages, $\mathbf{M'}_1$ and $\mathbf{M'}_2$ must be transferred over the channel. Let us assume that both messages share the same keystream. Then:

$$\mathbf{C}_1 = \mathbf{M'}_1 \oplus \mathbf{RC4}_{\mathbf{Key}}\mathbf{(Seed)}$$
$$\mathbf{C}_2 = \mathbf{M'}_2 \oplus \mathbf{RC4}_{\mathbf{Key}}\mathbf{(Seed)}$$

$\mathbf{C}_1$ and $\mathbf{C}_2$ are the two WEP encrypted messages, and **Seed** is the one employed for the RC4, as depicted in Figure 2 of the *Understanding the effective strength of the WEP* section. Then, it is possible to perform the following operation:

$$\mathbf{C}_1 \oplus \mathbf{C}_2 = (\mathbf{M'}_1 \oplus \mathbf{RC4}_{\mathbf{Key}}\mathbf{(Seed)}) \oplus (\mathbf{M'}_2 \oplus \mathbf{RC4}_{\mathbf{Key}}\mathbf{(Seed)}) = \mathbf{M'}_1 \oplus \mathbf{M'}_2 \qquad (1)$$

As a consequence, knowing $\mathbf{M'}_1$ (or $\mathbf{M'}_2$), allows to recover $\mathbf{M'}_2$ (or $\mathbf{M'}_1$). One might argue that the knowledge of a message $\mathbf{M'}_x$ is a tight hypothesis. However, being messages packets generated by some well-known protocol, it is possible to craft packets and send them via the Internet to a target host on the WLAN. Hence, the AP will encrypt the data for the attacker.

This kind of attack relies on relation (1). However, the operations in (1) are possible since both messages have been encrypted with the same **Seed**. To overcome this, IVs have been introduced, being them the only portion of the **Seed** that varies. Alas, IVs are only 24-bit long, hence it is likely that the same **Seed** will be sent over the network again.

The Oracle

In order to recover a relevant amount of known plaintext, the AP could be used as an *Oracle*, a device that unconsciously encrypts well-crafted packets for the attacker.

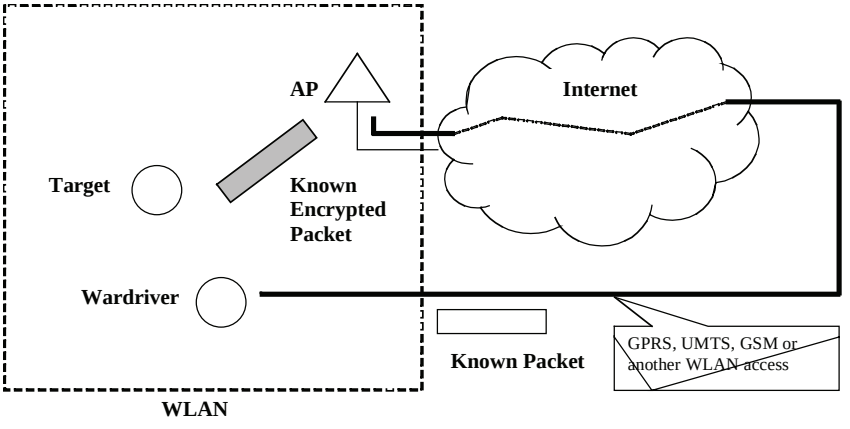
Figure 4 depicts the basic operations performed to conduct the attack. This attack is nowadays unlikely, since as explained, there are several faster and simpler ways to crack the WEP. Basically, the attacker exploits an active connection targeting the victim. Then he/she sends (e.g., via General Packet Radio Service [GPRS], or Universal Mobile Telecommunications System [UMTS], or similar) known packets that will be encrypted by the AP before transmission over the WLAN.

It becomes clear that this attack exploits the fact that an AP could be used to connect a network to the Internet without any further protection mechanism (e.g., a firewall or a virtual private network [VPN] support). For completeness, in early days when GPRS was expensive, usually the attack was performed by cooperating with another wardriver, usually at home, with an active Internet connection remotely injecting packets to the AP.

Decryption Dictionary

This kind of technique is no longer employed, and there are not any proofs that it has ever been exploited in its basic form. However, it is interesting that this attack allows (at least theoretically) the user to decrypt all the traffic without knowing the WEP key. Basically, it is sufficient to build a table of the intercepted keystreams. Then, it is possible to compile a table of all the possible values (and also skip the RC4 phase). The drawback, preventing its proficient exploitation, is the space required for this kind of attack. In fact, the encrypted

Figure 4. Scenario when an oracle attack is performed



stream is 1,500 bytes long at maximum, owing to the maximum MTU available, and the adoption of a 24-bit IV produces 16,777,216 (2^{24}) possible streams. Hence, the required space is 16,777,216 • 1500 = 23.4 Gbytes.

With the advent of PCMCIA cards, and their poor implementation of the policies to generate IVs, the adoption of a dictionary-based attack became feasible. In fact, many PCMCIA wireless cards reset the IV to 0 each time they are re-initialized. Re-initialization happens each time they are activated (e.g., typically once a day in many circumstances). Then it is sufficient to build a dictionary only for the very first values of IVs, in order to decrypt most of the flowing traffic.

Examples

In this section, we will present briefly some possible attacks against a WEP-secured network. Firstly, we will show how to attack a network by using KisMAC, a tool running on MacOSX with a simple GUI. Then we will show how to use standard terminal-based tools commonly available for different Unix flavors. As a remark, we will not spend too much time on explaining bruteforce or dictionary attacks. In fact, WEP could be cracked in a more elegant way; conversely, owing to its better security, we will explain bruteforcing and dictionary attacks in the section devoted to WPA. Such concepts could be straightforwardly extended also to WEP.

WEP Attack via KisMAC

Let us show an attack performed to a WEP-secured network. Firstly, we show how to crack a network with KisMAC. This gives an idea of how simple it might be. After launching KisMAC, one can start the scanning. If supported, one can select whether or not to adopt *passive* or active *scanning.* Figure 5 depicts the result of a scan.

Then, if there is the need of cracking the WEP, different actions could be performed. Firstly, one can try the Newsham's 21-bit attack, or try to bruteforce the WEP, but owing to the "information" conveyed by the IVs, quicker solutions could be adopted.

Two things may happen: (1) the network is experiencing a huge amount of traffic, hence producing a huge amount of IVs. In this perspective, an attacker must only wait to collect a sufficient number of IVs to perform a suitable attack; or (2) the network is under a low load, hence the time needed to collect a sufficient amount of IVs is non-negligible. Then, it is possible to stimulate traffic by using the de-authentication attack or injecting well-crafted packets; Figure 6 depicts

Figure 5. Scan result provided by the KisMAC tool

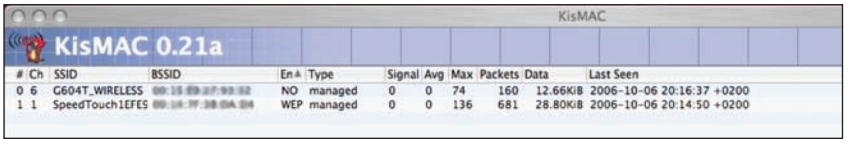


Figure 6. How to stimulate traffic in a WEP-secured network

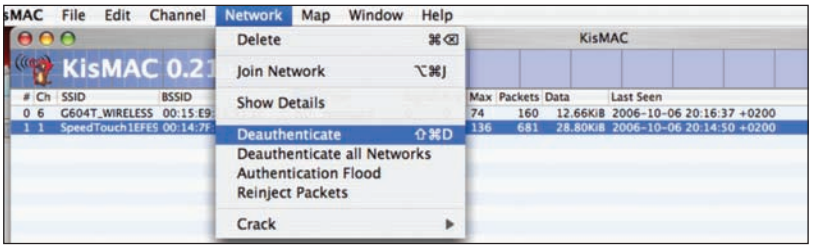


Figure 7. The network has been attacked with an authentication flood. Notice the random-generated MAC addresses.

Client	Vendor	Signal	sent Bytes	recv. Bytes
0C:B0:15:93:38:8F	unknown	127	90B	0
02:ED:5E:0B:9A:76	unknown	131	90B	0
06:08:8D:F6:B5:D8	unknown	129	90B	0
06:4C:25:E3:D0:B1	unknown	135	90B	0
0E:6E:DB:5D:20:37	unknown	131	90B	0
0A:7F:45:75:5D:D6	unknown	127	90B	0
0C:0C:63:9E:E3:11	unknown	131	90B	0
06:3F:E2:81:E0:3E	unknown	135	90B	0
00:C3:4C:0E:8B:03	unknown	135	90B	0
0C:F0:C6:05:DE:19	unknown	129	90B	0
08:55:86:4B:11:4F	unknown	127	90B	0
02:6B:09:67:4F:25	unknown	129	90B	0
0E:65:B9:D5:0E:A8	unknown	127	90B	0
0C:A9:94:C5:F5:9B	unknown	127	90B	0
0E:75:3C:E8:14:88	unknown	132	90B	0
08:98:A7:C6:27:52	unknown	131	90B	0
0A:64:F0:52:79:94	unknown	135	90B	0
02:84:84:F6:D6:2C	unknown	129	90B	0
06:0D:6B:17:F4:97	unknown	129	90B	0
02:A5:6C:76:B3:18	unknown	127	90B	0
06:7F:D8:E8:03:BA	unknown	129	90B	0
02:BA:D8:C3:51:47	unknown	129	90B	0
00:8E:F0:B5:D0:80	unknown	129	30B	0
08:40:9B:03:30:2C	unknown	129	90B	0
0E:C5:EA:50:13:AF	unknown	127	90B	0
00:2C:A9:10:91:92	unknown	129	90B	0
0E:DB:BD:ED:67:C9	unknown	129	90B	0
04:C3:A5:77:11:AE	unknown	129	90B	0
04:04:01:92:1E:69	unknown	127	90B	0
02:2F:54:7C:C9:C2	unknown	129	90B	0
08:B2:EA:45:90:73	unknown	133	90B	0
FF:FF:FF:FF:FF:FF	Broadcast	0	0B	13.07Ki

possible attacks to stimulate traffic, while Figure 7 depicts the "fake" stations that populate the attacked wireless network.

WEP Attack via Terminal-Based Tools

Firstly, let us start searching a network. For doing this, let us use *airodump*. Airodump allows to collect traffic from a wireless interface. It could be possible that you have *airodump-ng* instead, since it represents the evolution of the *aircrack* wireless suite. We will refer to the classical tool, since it could be possible that you already have it, especially if your configuration is not up-to-date; however, the concepts, as well as its usage, are the same.

Supposing the tool properly installed, it is sufficient to type in a terminal:

```
Mud:Luca$ ./airodump cardName theTrafficFile 0 loggingMode
```

Here, ./airodump launches the tool, cardName is the name of the card used to monitor the air, theTrafficFile is the output file collecting data. The parameter 0 specifies that we want to hop channels, while loggingMode allows to switch between logging all traffic or only IVs.

If we have collected enough IVs, we can try to crack the WEP by using *aircrack*. Some couple of remarks: (1) the traffic collection and the cracking phases are decoupled. Then you can perform an attack off-line (not hidden in a parking lot); (2) it is possible to collect data with well-known sniffers, such as *Wireshark* (formerly known as *Ethereal*). For instance, under Linux it is possible to use *airmon-ng* to configure the wireless card, then using *Wireshark* to collect traffic. By using *ivstool* from the *aircrack-ng* suite you can convert IVs from *.pcap* format to *aircrack* one.

Then, you can crack a network by typing:

```
Mud:Luca$ ./aircrack -b MAC theTrafficFile
```

Here, -b MAC specifies the MAC address (or the BSSID) of the target network. In fact, your dump could have collected traffic from different networks. The needed number of IVs varies: if your traffic dump is blessed, collecting 100,000 IVs suffices. Usually, the needed number of IVs ranges from 250,000 to 500,000. However, some advanced APs have algorithms that avoid the generation of weak IVs, hence reflecting in a huge number of needed IVs (in the order of several millions).

If there is not enough traffic on the network, collecting IVs could be a tedious (or at least time consuming) task. Moreover, if a sophisticated AP is employed, collecting 5,000,000 IVs with a traffic of few packets per second could be impossible.

Then, it is possible to stimulate traffic on the WLAN, in order to increase the number of packets sent, hence speeding up the collection of IVs.

For instance, by using the *aircrack* suite, it is possible to exploit the so-called address resolution protocol (ARP) *replay*.[2] Roughly, ARP relies on broadcasting a request (an ARP Request) for an IP address, in order to discover the matching between L2 and L3 addressing. The device that recognizes its IP address sends back a query directly to the original requestor. Alas, WEP does not assure protection against replay attacks. So you can inject well-crafted ARP packets and generate answers containing valid IVs. Needles to say, the more aggressive your ARP generation strategy is, the more packets you will collect (thus, reducing the time needed to collect a certain *x* amount of valid IVs).

To perform an *ARP replay* attack you can use the tool as follows (notice, that you must have also a sniffer running in order to capture replies).

```
Mud: Luca$ ./aireplay-ng --arpreplay -b MACAP -h TMAC Interface
```

./aireplay-ng launches the tool, the flag --arpreplay specifies to perform the ARP replay attack, -b MACAP specifies the MAC address of the AP and -h TMAC specifies the MAC of the target (victim) host. Lastly, Interface tells the program which wireless interface must be used.

If everything is correct, the attack starts generating more traffic.

WPA-PSK ATTACKS

WPA exists in different flavors: for enterprises and for home security. It offers many improvements compared to the WEP. Firstly, IVs are still adopted, but IVs are 48-bit long, preventing from IVs reuse or IVs collision. Secondly, IVs are checked before using them to encrypt packets.

The solution that WPA proposes for Enterprises is barely adequate to discourage any wardriving activities. But the version for home security could be compromised. As a remark, the WPA suite does not offer the ultimate toolkit for security.

As said, a consumer version of the WPA exists, and it is called WPA-PSK. Roughly, WPA-PSK performs similar steps like WEP, but it is more robust. Needles to say, owing to its easy set-up and cost effective implementation, it is often adopted as the basis of corporate security infrastructure. The main characteristic of the WPA-PSK that could be exploited by wardrivers is the "PSK portion" of the procedure. In the PSK, as the acronym suggests, the secret key is pre-shared, hence known a priori and stored in the equipment. However, the WPA-PSK during normal operations has some logic to change the codes and making break into the system a harder work.

In order to stick with the topic of wardriving, we will only explain the unique attack proven to be effective for the WPA-PSK.

The Handshake Attack

The basic under this attack is rooted in how the PSK is engineered. The PSK relies on a user-defined password to initialize the TKIP. From the attacker point of view, the TKIP is quite strong, owing its "*per packet*" nature. Nevertheless, the wardriving community has not yet found out how to crack it. As a consequence, in order to gain access to a WPA-PSK network, a direct attack to the TKIP will not give any reasonable results.

However, there is a weak point in the chain: the authentication. In fact, during the authentication, the requestor sends the PSK, to spawn the TKIP procedure that will cover the rest of the transmission.

The core of the exploit is based on the handshake for the following reason. Prior to starting a secure communication, the key must be sent over an insecure channel. Needles to say, to avoid sending the password in cleartext, thus resulting in a huge security breach in the procedure, there are several mechanisms (outside the scope of this chapter) employed to transmit the *passphrase* over the channel.

However, if a complete handshake is collected, it is possible to bruteforce the handshake procedure, and to recover the password. This attack has two main drawbacks (or advantages, depending on the viewpoint):

1. It is based on a bruteforce technique. If the password is strong enough, it is quite impossible to retrieve;
2. A complete handshake is needed. Without such information, all the traffic collected (even if several Gbytes) is needless.

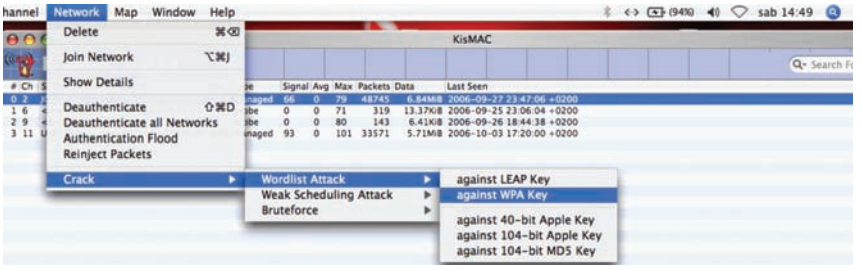
To overcome the previous drawbacks, some countermeasures are possible. Concerning 1), if in presence of a good dictionary that it is not limited to standard words, but also containing some well-known consumers' passwords, it is possible to bring into a feasible zone a bruteforce attack for some particular deployment (e.g., home network, where users tend to use weak passwords). Regarding 2), it is possible to force de-authentication of clients to collect the needed handshake traffic. However, at least one client must be present in the network to perform this attack. Besides, as explained previously, a wireless interface with packet injection capabilities is needed.

Example

In the *Weak IVs* section we showed some example by using the KisMAC software. KisMAC has a complete GUI, hence performing this attack solely implies to select it from the menu, as shown in Figure 8.

Notice that the Wordlist Attack against the WPA key is available only if a complete handshake has been collected.

Figure 8. WPA-PSK bruteforce attack when employing KisMAC



Instead of KisMAC, for pedagogical reasons, let us use *airodump*. Supposing the tool properly installed, it is sufficient to type in a terminal:

```
Mud:Luca$ ./airodump ath1 theTrafficFile 8
```

./airodump launches the program (./ to refer to a local path), ath1 specifies the interface where the traffic must be collected, TrafficFile specifies the file that will contain the traffic dump, and 8 is the channel to monitor. However, it is possible to force a de-authentication attack by specifying a flag to *airodump*.

Until there, we have only collected the traffic (and stimulated a complete handshake if needed). Now, it is possible to perform the off-line attack. Most of the tools can exchange data, so it is possible to collect data to *airodump* and perform the cracking procedure to KisMAC, cowpatty, …

Supposing we want to use *aircrack* we will use the tool (from the command line) in a form like:

```
Mud:Luca$ ./aircrack –a 2 –b MAC –w /Dictionary
```

./aircrack launches the tool, –a 2 specifies the attack, MAC is the MAC address of the AP to attack, –w specifies the path to a dictionary. For instance, many Unix systems have a minimal dictionary located in /usr/share/dict; you can preliminary start with this word collection. Notice that if the password is a standard dictionary, you should change it immediately, since it is very weak and predictable.

Lastly, another interesting tool (even if quite slow) is cowpatty. In order to crack a WPA key with cowpatty, you will use the tool like:

```
Mud:Luca$ ./cowpatty –f Dictionary –r theTrafficFile –s wpa
```

where ./cowpatty launches the software, –f specifies the dictionary (a file called Dictionary in this example), –r specifies where the traffic dump is located (theTrafficFile here) and –s wpa tells the program to crack against the WPA.

Concluding, if a proper handshake is collected, with the aforementioned tools it is possible to crack the WPA. As shown, the steps are not complex. Then, it is possible to understand the *importance of the password*, since it is the only barrier preventing your network to be cracked.

SOME THOUGHTS ABOUT THE WARDRIVERS COMMUNITY

In the following subsections, some ideas on why the wardriving community deserves attention are presented. Besides, always remember that many flaws of the WEP arose due to the fact that it has been developed without any “open” review.

Monitor the Internet Community

The Internet community does not only produce tools, but also important information regarding concepts of security and wardriving. Three major resources are suggested for periodic surveys:

1. Wardriving sites that publish the location of a network (that could be precisely located, as explained in Section I by using a GPS);

a smart step could be to investigate sites publishing WLANs, in order to discover if yours has been detected and cracked.

2. Check for (almost weekly) security bulletins (e.g., BugTraq). Gears are composed not only by hardware, but also software (e.g., the firmware) that could have vulnerabilities. For instance, one of the most famous was related to an AP that upon receiving a broadcast user datagram protocol (UDP) packet on port 27155 containing the string "getsearch" returned (in clear) the WEP keys, the MAC filtering database and the admin password (a big prize, indeed).
3. Periodically download and try the tools. It is useful, funny, and gives an idea of the activity of the underground community.

Avoid Default Configurations (Always)

It is widely known that default configurations are most of the time fine for normal users, but not particularly tweaked for security. For instance, in the *Wireless power* section we discussed some possible risks arising when too much transmission power is employed. Besides, another threat relies in default names for the SSID, which can be employed to uncloak a hidden network, even if without special tools. For instance, it is well known that many Cisco AP use "*tsunami*" as default SSID, and that Linksys uses "*linksys.*" Nevertheless, it is possible to retrieve them by performing a simple Web search (moreover it is possible to retrieve SSID naming schemas for hotels, retailers, and popular Internet cafès…). Lastly, a good suggestion is to change also the default password of your gear, since a malicious attacker (that normally is not a wardriver, but a vandal) can try to alter the AP configuration.

Browse the Source and Use the Tools

Owing to the availability of the tools, it is a better idea to try to be a wardriver sometimes, in order to test your own set-up, as well as the configuration made by your users (e.g., students, colleagues, or customer). Besides, studying the tools and collecting the traces is mandatory to discover possible attacks, for instance by recognizing unusual probes or excessive de-association requests.

Do Not Rely on Weak Passwords

As explained in previous section, bruteforcing a WLAN will be always possible. WEP makes bruteforcing to be useless (owing to its flaws), but WPA-PSK can be only exploited by using a dictionary attack. Hence, the strength of your WLAN depends on the password. Use a good policy to create and distribute passwords and change them often. Do not forget that hundreds of people collaborate to produce dictionaries with most popular passwords, also the most disparate ones (and also in leet variant – *l33t v4r1aNt*).

TOOLS

NetStumbler (www.netstumbler.com): NetStumbler is a program for the Windows™ operating system allowing to detect WLANs. It is a quite handy tool for locating WLANs but it has not all the features and the flexibility of the Aircrack-ng suite.

Kismet (www.kismetwireless.net): Kismet allows monitoring and sniffing traffic over a WLAN. In addition, it can also be adopted as an intrusion detection system. Kismet is able to identify networks both in active and passive mode. Besides, it also offers many other features, such as BSSID uncloaking. Kismet supports many wireless cards and many OSs, as well as many CPUs (e.g., x86, ARM, PPC, and X-Scale); however, some features are only available on the Linux-x86 version.

KisMAC (http://KisMAC.de/): KisMAC is the counterpart of Kismet, but it runs natively on MacOSX and it is easy to use, owing to its simple GUI.

Aircrack-ng (http://www.aircrack-ng.org): Aircrack-ng is a comprehensive suite of tools, ranging from analyzers, sniffers, and cracking tools. Sources and scripts are available, promoting aircrack-ng as one of the best tools and a starting

Table 3. Summary of wardriving threats and possible countermeasures

Attack - Detected Anomaly	Skills Needed	WLAN Affected	Security Risk	Countermeasures
SSID uncloack	None. Automatically done in several software	ALL	1	None at this level.
Active scan	None. Automatically done by interfaces' drivers	ALL	0	Forecasted in the standard. Check periodically MAC addresses of traffic flows.
Passive scan	None, but proper software and a proper interface is needed.	ALL	2	Reduce the transmission power.
WEP crack	Minimum	If WEP Protected	10	Avoid WEP. If WEP must be in place (for legacy support) change password often. Monitor traffic to detect peaks and activate MAC filtering (at least). Force users to adopt VPN and disable DHCPs.
MAC spoofing	Medium. Kernel patches could be needed.	ALL	8	MAC-based policies must be adopted jointly with encryption techniques.
Packet injection	Medium.	If WEP Protected	5	Tools for performing packet injection can also monitor the WLAN like IDS.
De-authentication flood	Medium	For WPA	7	The attacker could be "serious." Change the WPA password to avoid a dictionary attack.
Unsolicited traffic in indoor environments	Medium/High	ALL	9	When in presence of limited transmitting power, the attacker relies on high gain antennas, thus could be a prepared attacker.
Unrecognized	High	ALL	10	It could be a "false positive" or the attacker could be able to produce his/her own tools.

point for developing automated (e.g., *cron-drived*) or tweaked wardriving tools.

SUMMARY TABLE ABOUT WARDRIVING ATTACKS

In this section, we summarize many security threats deriving from wardrivers' activity, by offering a comprehensive table. In addition, we will also introduce some "security risks" in order to better calibrate the needed countermeasures. Security risks have been quantified on a range varying from 0 (none) to 10 (severe). However, the more security is employed in the WLAN, the better. But, being *wardriving* tightly mixed with people habits and urban culture, the exposures to risks may vary according where the WLAN is placed. Table 3 contains the summary.

CONCLUSION

In this chapter we introduced the concept of wardriving, and practices related to cracking wireless networks. As explained, cracking a WLAN is not a complex task: then, for your security you should rely on other techniques (e.g., RADIUS). In addition, by using examples, it is possible to produce your own penetration tests, as well as exercises to show some real world attack to students and engineers.

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KEY TERMS

Active Mode: Active mode is an operative mode where scanning is done via probe packets. As a consequence, the scanner does not remain undetected.

MAC Address Filtering: MAC address filtering is a technique that allows/denies network accesses only for a predefined MAC address.

MAC Spoofing: MAC spoofing is changing the MAC of the L2 interface. Typically it is employed to by-pass MAC address filtering.

Packet Injection: Packet injection is the activity of inserting a packet in a network for some purpose. For instance, when attacking a WEP-protected network, to stimulate the traffic production to gain more data to be analyzed.

rfmon: rfmon is an operative mode of IEEE 802.11-based air interfaces, allowing to scan for access points while remaining undetectable, since the card does not send any probe packets.

Wardriving: Wardriving is the activity of "*driving around, looking for wireless networks.*"

Wired Equivalent Privacy (WEP): WEP is an encryption mechanism with many security flaws. Recognized as a real security issue, it has been replaced by wireless protected access (WPA).

ENDNOTES

1 However, if raw frames are supported by the internal chipset, you can always build your own tools and enabling drivers by investigating the data-sheets.

2 Many OSes or firmware clear the ARP cache upon disconnection. Then, it could be useful to use a more "aggressive" strategy, as suggested in aircrack documentation.

Chapter VI
Intrusion and Anomaly Detection in Wireless Networks

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ABSTRACT

The broadcast nature of wireless networks and the mobility features created new kinds of intrusions and anomalies taking profit of wireless vulnerabilities. Because of the radio links and the mobile equipment features of wireless networks, wireless intrusions are more complex because they add to the intrusions developed for wired networks, a large spectrum of complex attacks targeting wireless environment. These intrusions include rogue or unauthorized access point (AP), AP MAC spoofing, and wireless denial of service and require adding new techniques and mechanisms to those approaches detecting intrusions targeting wired networks. To face this challenge, some researchers focused on extending the deployed approaches for wired networks while others worked to develop techniques suitable for detecting wireless intrusions. The efforts have mainly addressed: (1) the development of theories to allow reasoning about detection, wireless cooperation, and response to incidents; and (2) the development of wireless intrusion and anomaly detection systems that incorporate wireless detection, preventive mechanisms and tolerance functions. This chapter aims at discussing the major theories, models, and mechanisms developed for the protection of wireless networks/systems against threats, intrusions, and anomalous behaviors. The objectives of this chapter are to: (1) discuss security problems in a wireless environment; (2) present the current research activities; (3) study the important results already developed by researchers; and (4) discuss the validation methods proposed for the protection of wireless networks against attacks.

INTRODUCTION

Wireless has opened a new and exciting area for research. Its technology is advancing and changing every day. However, the biggest concern with wireless has been security. For some period of time, wireless has seen very limited security on the wide open medium. Along with improved encryption schemes, a new solution helping the problem resolution is the *wireless intrusion detection system* (WIDS). It is a network component aiming at protecting the network by detecting *wireless attacks*, which target *wireless networks* having specific features and characteristics. Wireless intrusions

can belong to two categories of attacks. The first category targets the fixed part of the wireless network, such as MAC spoofing, IP spoofing, and denial of service (DoS); and the second category of these attacks targets the radio part of the wireless network, such as the access point (AP) rogue, noise flooding, and wireless network sniffing. The latter attacks are more complex because they are hard to detect and to trace-back.

To detect such complex attacks, the WIDS deploys approaches and techniques provided by intrusion detection systems (IDS) protecting wired networks. Among these approaches, one can find the signature-based and *anomaly* based approaches. The first approach consists in matching user's patterns with stored attack's patterns (or signatures). The second approach aims at detecting any deviation of the "normal" behavior of the network entities. The deployment of the aforementioned approaches in a wireless environment requires some modifications. The signature-based approach in wireless networks may require the use of a knowledge base containing the wireless attack signatures while an anomaly based approach requires the definition of profiles specific to wireless entities (mobile users and AP). Recently, efforts have focused on *wireless intrusion detection* to increase the efficiency of WIDS. Based on these efforts, models and architectures have been discussed in several research works.

The objective of this chapter is to discuss the major research developments in wireless intrusion detection techniques, models, and proposed architectures. Mainly, the chapter will: (1) discuss security problems in wireless environments; (2) present current research activities; (3) study important results already developed; and (4) discuss validation methods proposed for WIDS. The remaining part is organized as follows: The next section discusses *vulnerabilities,* threats, and attacks in wireless networks. The third section presents wireless intrusion and anomaly detection approaches. The fourth section introduces models proposed for detecting wireless intrusions. The fifth section presents WIDS architectures, proposed by researches papers. The sixth section presents the wireless distributed schemes for intrusion detection. The seventh section discusses mechanisms of *prevention* and *tolerance* provided to enhance the wireless intrusion detection. Finally, the last section concludes the chapter.

VULNERABILITIES, THREATS, AND ATTACKS IN WIRELESS NETWORKS

To present vulnerabilities, threats, and attacks targeting wireless networks, we have to discuss first the security requirements of wireless systems, including those concerning security policy. This section presents the concepts of wireless intrusion, anomaly, and attack scenario in wireless networks, in order to highlight intrusion and anomaly detection requirements. In particular, it discusses some attacks and attack classification that make security in wireless systems very special.

Security Requirements in Wireless Environments

Securing a communication channel should satisfy at least the following set of requirements: integrity, confidentiality, and availability. Moreover, wireless communications require authentication of the sender or/and the receiver and techniques that guarantee non-repudiation. In the following, we discuss technical security and security policy requirements which help reducing vulnerabilities and attack damages.

Because of their technical architecture, mobile communications are targets for a large set of threats and attacks that occur in wired networks, such as identity spoofing, authorization violations, data loss, modified and falsified data units, and repudiation of communication processes. Additionally, new security requirements and additional measures for wireless networks have to be added to the security requirements of wired networks (Schäfer, 2003). Vulnerabilities, threats, and attacks, existing in wireless networks represent a greater potential risk for wireless networks. One among technical requirements is the enforcement of security of the wireless links, because of the ease of gaining direct physical accesses. Moreover, new difficulties

can arise in providing wireless security services. For example, the authentication of a mobile device has to be verified by (or for) all AP (or base station [BS]) under which the mobile changes its localization. Because of the handover, respective entities cannot be determined in advance, so the key management process is more complicated. Also, the difference with wired networks, in terms of confidentiality of mobile device location, reveals a number of threats against mobile communications. This appears because of the following conflict: In one hand, each mobile should be reachable for incoming communication requests while, on the other hand, any network entity should be able to get the current location of a mobile device in the network (Schäfer, 2003).

Wireless Vulnerabilities and Threats

A vulnerability is a weakness (or fault) in the communication medium or a protocol that allows compromising the security of the network component. Most of the existing vulnerabilities in the wireless medium are caused by the medium. Because transmissions are broadcast, they are easily available to anyone who has the appropriate equipment. Particular threats of the wireless communication are device theft, malicious hacker, malicious code, theft of service, and espionage (Boncella, 2006). There are numerous of wireless vulnerabilities and threats that are studied in the literature, for the purpose of detecting attacks exploiting them. In the following, we distinguish two categories of vulnerabilities and threats: those existing in a LAN-like wireless networks (WLAN) and those existing in cellular-like wireless networks (Hutchison, 2004).

WLAN Vulnerabilities and Threats

The following are typical vulnerabilities existing in the main component of WLAN, which is the AP.

- **Signal range of an authorized AP:** This vulnerability is about the possibility of the extension of AP signal strength beyond a given perimeter. Consequently, the AP's placement and signal strength have to be adapted to make sure that the transmitting coverage is just enough to cover the correct area.
- **Physical security of an authorized AP:** Because most APs are mounted by default, their placement is critical. An AP has to be correctly placed in order to avoid accidental damage, such as direct access to the physical network cable. To protect physically the access to the AP, many solutions were proposed; but all of them require a mandatory policy.
- **Rogue AP:** This vulnerability is a sort of man-in-the middle attack, where an attacker can place an unauthorized (or rogue) AP on the network and configure it to look legitimate to gain access to wireless user's sensitive data. This can be done because user's devices need to be connected to the strongest available AP signal.
- **The easy installation and use of an AP:** In order to use the advantages of internal networks, employees can introduce an unauthorized wireless network. The easy installation and configuration of the AP make this feasible for legitimate or illegitimate users.
- **The AP configuration:** If the AP is poorly configured or unauthorized, then it can provide an open door to hackers. This is caused by using a default configuration that annihilates the security controls and encryption mechanisms.
- **Protocol weaknesses and capacity limits on authorized AP's:** These limitations can cause DoS from hackers using unauthorized AP's when they can flood authorized AP with traffic forcing them to reboot or deny accesses.

Some of the attacks, exploiting the aforementioned vulnerabilities are discussed in the following section of this chapter.

Cellular System Vulnerabilities and Threats

This subsection presents cellular system vulnerabilities and threats that are categorized as follows (Nichols & Lekkas, 2002):

- **Service interruption:** The increased capacity provided by the high-speed technology has resulted in fewer cable routes necessary to meet capacity requirements. Consequently, this has decreased the number of switches. The lack of overall diversity in cabling and switching has increased the vulnerability of telecommunication infrastructures. This can cause DoS of an entire zone.
- **Natural threats:** Natural threats comprise the category of repeated threats caused by climatic, geological, or seismic events. Severe damage resulting from natural disaster can cause long-term damage to the telecommunication infrastructures.
- **Handset vulnerabilities:** Unlike computer systems, handsets are limited regarding the security features. Because wireless messages travel through the air by passing conventional wired network for transmission to the receiver, messages may need to be changed to another protocol (e.g., at the gateway, the *wireless transport layer security* message has to be changed to *Secure Socket Layer*). This operation presents vulnerability because anyone can access the network at this moment. Moreover, the use of encryption can add vulnerabilities, which can make confusion between mobile phones, since the node does not know its encrypted true location.

Wireless Attacks

Detecting a large set of attacks by a WIDS requires studying and developing the attacker's methods and strategies. We discuss in this subsection the typical attacks and malicious events that can be detected by a WIDS (Hiltunen, 2004; Vladimirov, Gavrilenko, & Mikhailovsky, 2004).

Illicit Use

Illicit use of a wireless network may involve an attacker connecting to the Internet or to the corporate network that lives behind the AP. Illicit use is a passive attack that does not cause damage to the physical network. It includes following attacks (Mateli, 2006):

- **Wireless network sniffing:** When wireless packets traverse the air, attackers equipped with appropriate devices and software can capture them. Sniffing attack methods include:
  - **Passive scanning:** This attack aims at listening to each channel. It can be done without sending information. For example, some radio frequency monitors can allow copying frames on a channel.
  - **Service set identifier (SSID) detection:** This consists in retrieving SSID by scanning frames of the following types: beacon, probe requests, probe responses, association requests, and re-association requests.
  - **MAC addresses collecting:** To construct spoofed frames, the attacker has to collect legitimate MAC addresses, which can be used for accessing AP filtering out frames with non registered MAC addresses.

To capture wireless packets, specific equipments should be used by the attackers, depending on the targeted wireless network interface card (Low, 2005).

- **Probing and network discovery:** This attack aims to identify various wireless targets. It uses two forms of probing: active and passive. Active probing involves the attacker actively sending probe requests with no identification using the SSID configured in order to solicit a probe response with SSID information and

other information from any active AP. When an attacker uses passive probing, he is listening on all channels for all wireless packets, thus the detection capability is not limited by the transmission power (Low, 2005).

- **Inspection:** The attacker can inspect network information using tools like Kismet and Airodump (Low, 2005). He could identify MAC addresses, IP address ranges, and gateways.

Wireless Spoofing

Spoofing purpose is to modify identification parameters in data packets. New values of selected parameters can be collected by sniffing. Typical spoofing attacks include:

- **MAC address spoofing:** MAC spoofing aims at changing the attacker's MAC address by the legitimate MAC address. This attack is made easy to launch because some client-side software allows the user to view their MAC addresses.
- **IP spoofing:** IP spoofing attempts to change source or destination IP addresses by talking directly with the network device. IP spoofing is used by many attacks. For example, an attacker can spoof the IP address of host A by sending a spoofed packet to host B announcing the window size equal to 0; though, it originated from B (Mateli, 2006).
- **Frame spoofing:** The attacker injects frames having the 802.11 specification with spoofed containing. Due to the lack of authentication, spoofed frames cannot be detected.

Man in the Middle Attacks

This attack attempts to insert the attacker in the middle (man in the middle [MITM]) of a communication for purposes of intercepting client's data and modifying them before discarding them or sending them out to the real destination. To perform this attack, two steps have to be accomplished. First, the legitimate AP serving the client must be brought down to create a "difficult to connect" scenario. Second, the attacker must setup an alternate rogue AP with the same credentials as the original for purposes of allowing the client to connect to it. Two main forms of the MITM exist: the eavesdropping and manipulation. Eavesdropping can be done by receiving radio waves on the wireless network, which may require sensitive antenna. Manipulation requires not only having the ability to receive the victim's data but then be able to retransmit the data after changing it.

Denial of Service Attacks

DoS attacks can target different network layers as explained in the following:

- **Application layer:** DoS occurs when a large amount of legitimate requests are sent. It aims to prevent other users from accessing the service by forcing the server to respond to a large number of request's transactions.
- **Transport layer:** DoS is performed when many connection requests are sent. It targets the operating system of the victim's computer. The typical attack in this case is a SYN flooding.
- **Network layer:** DoS succeeds, if the network allows to associate clients. In this case, an attacker can flood the network with traffic to deny access to other devices. This attack could consist of the following tasks:
  - The malicious node participates in a route but simply drops several data packets. This causes the deterioration of the connection (Gupta, Krishnamurthy, & Faloutsos, 2002).
  - The malicious node transmits falsified route updates or replays stale updates. These might cause route failures thereby deteriorating performance.
  - The malicious node reduces the time-to-live (TTL) field in the IP header so that packets never reach destinations.
- **Data link layer:** DoS targeting the link layer can be performed as follows:

  - Since we assume that there is a single channel that is reused, keeping the channel busy in the node leads to a DoS attack at that node.
  - By using a particular node to continually relay spurious data, the battery life of that node may be drained. An end-to-end authentication may prevent these attacks from being launched.
- **Physical layer:** This kind of DoS can be executed by emitting a very strong RF interference on the operating channel. This will cause interference to all wireless networks that are operating at or near that channel.

WIRELESS INTRUSION AND ANOMALY DETECTION

This section discusses the major security solutions provided for wireless networks. In particular, the cases of WLAN and ad hoc networks will be addressed. The discussed methods include the radio frequency fingerprinting, cluster-based detection, mobile devices monitoring, and mobile profile construction.

Basic Techniques for Detection

Wireless intrusion detection protects wireless networks against attacks, by monitoring traffic and generating alerts. Two ways of detection are distinguished: signature based and anomaly based. The first category aims at detecting known attacks by looking for their signatures. The main disadvantage of such approaches is that they detect only known attacks. The anomaly based approaches are not often implemented, mostly because of the high amount of false alarms that have to be managed loosing a large amount of time. Anomaly based detection develops a baseline of the way of considering normal traffic. When an abnormal traffic is detected, an alert is generated. The advantage of such approach is that it can capture unknown attacks.

To take from the advantages of the previous two approaches, the hybrid approach consists on using in the same system the two approaches simultaneously. To be efficient, intrusion detection approaches has to be run online and in real time. Otherwise, the use of intrusion detection technique is useful for audit or postmortem digital investigation and it will not prevent an attack on time. Real-time intrusion detection has to be able to collect data from the network in order to store, analyze and correlate them, which can decrease network performance (Hutchison, 2004).

Wireless Detection Approaches

The main objective of wireless detection is to protect the wireless network by detecting any deviation with respect to the security policy. This can be done by monitoring the active components of the wireless network, such as the APs (Hutchison, 2004). Generally, the WIDS is designed to monitor and report on network activities between communicating devices. To do this, the WIDS has to capture and decode wireless network traffic. While some WIDSs can only capture and store wireless traffic, other WIDSs can analyze traffic and generate reports. Other WIDSs are able to analyze signal fingerprints, which can be useful in detecting and tracking rogue AP attack. As it is done for wired networks, the following classifications of IDSs can be distinguished according to several dimensions: the approach (signature based/anomaly based); the monitored system (network-based/host-based); and the way of response (active/passive).

Mobile Profiles Construction

The main objectives when using the anomaly based approach are to define user mobility profiles (UMPs) and design an appropriate system that permits the detection of any deviation with respect to UMP. The intrusion detection process begins with the data collection processing. Once the user location coordinates (LCs) are determined, a high-level mapping (HLM) is applied. The objective of the HLM is to decrease the granularity of the data in order to accommodate minor deviations or intra-user variability between successive location broadcasts. LCs features are extracted from each

broadcast during feature extraction. A set of these chronologically ordered LCs are subsequently concatenated to define a mobility sequence (Hall, Barbeau, & Kranakis, 2005). This process continues until the creation of the mobility sequences. The training patterns from the first four of the six data set partitions are stored in the UMP, along with other user-related information. During the classification phase, a set of user mobility sequences are observed and compared to the training patterns in the user's profile to evaluate the similarity measure to profile (SMP) parameter. If the average of the SMP value exceeds predefined thresholds, then the mobility sequences are considered abnormal and an alert is generated (Hall et al., 2005).

The following parameters are defined for the mobility profiles: (1) the identifier representing the user identification; (2) the training patterns characterizing the user mobility behavior; (3) the window size representing the mobility sequence numbers (SN).

Monitoring Wireless Devices

Using a signature-based approach, the IDS bases its processing on the recognition of intrusion's patterns from the traffic outputs. This requires monitoring several parameters of the AP outputs and the wireless client. Monitoring APs is about monitoring their respective SSID, MAC address, and channel information. This requires listening wireless frames, such as beacons, probe response, and authentication/association frames at the AP outputs and comparing them to the predefined attack signatures. For example, in the case of MITM attack, the monitoring process would detect that there is a sudden introduction of an AP on another channel previously not present. Through the SSID, MAC address might be spoofed by the attacker in the process of setting up the rouge AP.

Because authorized clients cannot be listed, the information that may help detecting an attack cannot be totally available; nevertheless, the following aspects can be monitored (Low, 2005):

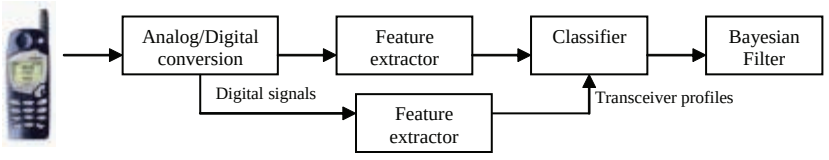
- The "blacklist" of wireless clients can be checked against all connecting clients. Any client within this list trying to access the network would be automatically denied and an alert can be sent off.
- All wireless clients with an "illegal" MAC address (MAC address ranges, which have not been allocated) are automatically denied access and an alert is sent off.
- A wireless client that just sends out probe requests or special distinguishable data packets after the initial probe request has not been authenticated can be flagged out as potential network discovery attack.
- Usually, when impersonation attacks are ongoing, the attacker will take on the MAC/IP address of the victim, but it will not be able to continue with the SN used previously by the victim. Thus, by monitoring the SN in these packets, potential impersonators could be identified.

Radio Frequency Fingerprinting (RFF)

The RFF is defined as the process identifying a cellular phone by the unique "fingerprint" that characterizes its signal transmission. It is used to prevent cloning fraud, because a cloned phone will not have the same fingerprint as the legal phone with the same electronic identification numbers. This approach aims to enhance the anomaly based wireless intrusion detection by associating a MAC address with the corresponding transceiver profile. The architecture of the corresponding IDS is shown by Figure 1, where the main objective is to classify an observed transceiver print as normal (belongs to the transceiver of a device with a given MAC address) or anomalous (belongs to another transceiver) (Barbeau, Hall, & Kranakis, 2006; Hall et al., 2005).

As illustrated in Figure 1, the information flow begins by converting the analog signal to a digital signal. This is done by the converter component. Second, the transient extractor extracts the transient portion from the digital signal. Then, the amplitude, phase, and frequency defining the transceiverprint are extracted by the feature extraction component. These features are compared to the transceiver profiles existing in the IDS. This operation is

Figure 1. The enhanced architecture of WIDS



performed by the classifier component. To decide about the status of the transceiverprint, the Bayesian filter is applied. This process requires extracting predefined transceiver's profiles, which is detailed in the following sub-section.

- **Feature extractor:** In this step, amplitude and phase components are obtained using respectively, equations (1) and (2).

$$a(t) = \sqrt{i^2(t) + q^2(t)} \quad (1)$$

$$\theta(t) = \tan^{-1}[\frac{q(t)}{i(t)}] \quad (2)$$

  Frequency extraction is done by applying the discrete wavelet transform (DWT), for example.
- **Classifier:** To classify a signal as anomalous, the probability of match has to be determined for each transceiver profile. Therefore, a statistical classifier using neural networks can be used, where the set of extracted features represent a vector and the outputs are a set of matching probabilities.
- **Bayesian filter:** To decide whether matching probabilities exceed threshold values, a Bayesian filter is applied because of the noise and interference, which are special characteristics of wireless environment. The Bayesian filter has to estimate the state of a system from noisy observations.
- **Feature selection/profile definition:** Before applying the detection process, the definition of transceiver's profiles has to be made. To do so, features that have low intra-transceiver variability and high inter-transceiver variability are selected. Examples of selected features include: deviations of normalized amplitude, phase and frequency, amplitude variance, and deviations of normalized in-phase data and normalized quadrate data.

Cluster-Based Detection in Ad Hoc Networks

Due to the distributed nature of wireless networks, especially ad hoc networks are vulnerable to attacks. In this case, intrusion detection provides audit and monitoring capabilities that offer local security to a node and helps to perceive specific trust levels of other nodes (Ahmed, Samad, & Mahmood, 2006; Samad, Ahmed, & Mahmood, 2005). Clustering protocols can be taken as an additional advantage in these processing constrained networks to collaboratively detect intrusions with less power usage and minimal overhead. Because of their relation with routes, existing clustering protocols are not suitable for intrusion detection. The route establishment and route renewal and route renewal affect clusters. Consequently, processing and traffic overhead increase, due to instability of clusters. Ad hoc networks present battery and power constraint. Therefore, the monitoring node should be available to detect and respond against intrusions in time. This can be achieved only if clusters are stable for a long time period. If clusters are regularly changed due to routes, the intrusion detection will not be efficient. Therefore, a generalized clustering algorithm, detailed in Ahmed et al. (2006) has been discussed. It is also useful to detect collaborative intrusions (Samad et al., 2005).

Cluster Formation

Clusters are formed to divide the network into manageable entities for efficient monitoring and low processing. Clustering schemes result in a

special type of node, called the cluster head (CH) to monitor traffic within its cluster. It not only manages its own cluster, but also communicates with other clusters for cooperative detection and response. It maintains information of every member node (MN) and neighbor clusters. The cluster management responsibility is rotated among the cluster members for load balancing and fault tolerance and must be fair and secure. This can be achieved by conducting regular elections (Samad et al., 2005). Every node in the cluster must participate in the election process by casting their vote showing their willingness to become the CH. The node showing the highest willingness, by proving the set of criteria, becomes the CH until the next timeout period.

Intrusion Detection Architecture

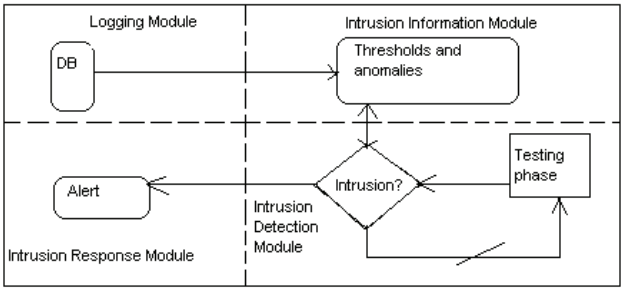
Because ad hoc networks lack in centralized audit points, it is necessary to use the IDS in a distributed manner. This also helps reducing computation and memory overhead on nodes. The proposed clustering algorithm in Samad et al. (2005) can be related to the intrusion detection process as partial analysis of the incoming traffic is done at the CH and the rest of the analysis is done at the destination node. Traffic analysis at the CH and packet analysis at the MN is helpful in reducing processing at each node. If a malicious activity is found by the CH, it informs its members and the neighboring clusters to take a set of actions. It is the responsibility of CH to obtain help from and/or inform the MNs and neighboring clusters for a particular intrusion. Undecided node (UD) performs its own audit and analysis; however, it performs partial analysis immediately after becoming a CH or MN. Intrusion detection techniques can be anomaly based or signature based.

The host-based IDS (HIDS) observes traffic at individual hosts, while network-based IDS (NIDS) are often located at various points along the network. Since centralized audit points are not available in ad hoc networks, NIDSs cannot be used. Alternatively, if every host starts monitoring intrusions individually such as in HIDS, lot of memory and processing will be involved. Therefore, a distributed approach is used to perform monitoring, where both CH and MN collect audit data.

A flow model of intrusion detection architecture of cluster-based intrusion detection (CBID) is illustrated by Figure 2, which consists of four modules. Information collected during the training phase in the logging module is transferred to the intrusion information module to perceive a threshold value for the normal traffic. If it is the case, an alert is generated by the intrusion response module.

- **Logging:** The CH captures and logs all the traffic transferred through its radio range. It keeps the necessary fields and the data related to traffic such as number of packets sent, received, forwarded, or dropped in a database. The traffic can either be data traffic or control traffic. These logs can be helpful for the detection of many attacks, such as blackhole, wormhole, sleep deprivation, malicious flooding, packet dropping, and so forth.
- **Intrusion information:** If signature-based detection is used, every node must maintain

Figure 2. Intrusion detection process



a database that contains all the intrusion signatures. For anomaly based detection, the anomalous behaviors must also be well defined.

- **Intrusion detection:** By this module, the node detects intrusions by analyzing and comparing the traffic patterns with the normal behavior. If anomaly is found, the CH generates an alarm and increases the monitoring level and analyzes the traffic in more detail to find out the attack type and identity of the attacker.
- **Intrusion response:** To inform about detected intrusions, nodes generate alerts. They also can provide responses to react against them.

DETECTION MODELS

To enhance IDS efficiency, theories and models have been developed to cope with intrusion correlation; action tracking and packet marking; digital investigation using evidences based on alerts; and attack reconstruction in wireless environments. The evidence is defined as a set of relevant information about the network state (Aime, Calandriello, & Lioy, 2006).

Intrusion and Anomaly Detection Model Exchange

This section discusses the anomaly model used in mobile ad hoc networks (MANET). It is based on the model distribution and model profiling and aggregation.

Model Distribution

Due to the lack of battery power or computation ability, MANET's model is required. Depending on the node location performing intrusion detection, the following distribution models can be adopted (Cretu, Parekh, Wang, & Stolfo, 2006):

- In the case of generating anomalies, training can be done by MANET nodes: (1) if the MANET nodes have WAN connectivity, the node can initiate download requests to obtain the latest model from the server; and (2) without WAN connectivity, MANET nodes can be initialized before deployment, where the default model is used.
- Another model consists in deploying a more powerful MANET node with sufficient processing and battery power to perform anomaly training. The node would listen promiscuously to all visible traffics on the MANET, generate anomalies, and distribute them to the peers.
- Use a pre-computed anomaly model. This scenario is worst case, but can be practical in situations where the MANET's behavior is well-defined and follows a standard protocol definition.

Model Aggregation/Profiling

The aggregation model was previously used in MANETs for alerts demonstrated that, by integrating security-related information at the protocol level from a wider area, the false positive rate and the detection rate can be improved (Cretu et al., 2006).

In addition, model aggregation enables peers to determine whether or not to communicate with a particular node $\boldsymbol{n_1}$. If the peers' models are very similar to those used by $\boldsymbol{n_1}$, it suggests that the node is performing similar tasks. A node with a dissimilar model is considered as suspicious and has a malicious content. For example, a node sending out worm packets will generate a substantially different content distribution. This can be done via comparison (Cretu et al., 2006).

Anomaly Based Detection Models

In this section, we discuss how to build anomaly detection models for wireless networks. Detection based on different kinds of activities may differ in the format and the amount of available audit data as well as the modeling algorithms. However, we admit that the principle behind the approaches will be the same. Therefore, we discuss in this section

only one of these approaches, which is based on a routing protocol (Zhang, Lee, & Huang, 2003):

Building an Anomaly Detection Model

This method uses information-theoretic measures, namely, entropy and conditional entropy, to describe normal information flows and use classification algorithms to build anomaly detection models. When constructing a classifier, features with high information gain or reduced entropy are needed. Therefore, a classifier needs feature value tests to partition the original dataset into low entropy subsets. Using this framework, the following procedure for anomaly detection is applied (Zhang et al., 2003): (1) select audit data so that the normal dataset has low entropy; (2) perform appropriate data transformation according to the entropy measures; (3) compute classifier using training data; (4) apply the classifier to test data; and (5) post-process alarms to produce intrusion reports.

Detecting Abnormal Updates to Routing Tables

The main requirement of an anomaly detection model used by IDSs is a low false positive rate, calculated as the percentage of legitimate behavior variations detected as anomalies. Since the main concern for ad hoc routing protocols is that the false routing information generated by a compromised node will be disseminated to and used by the other nodes, the trace data can be designed for each node. A routing table contains, at the minimum, the next hop and the distance in hop number. A legitimate change in the routing table can be caused by the physical node movement or network membership changes. For a node, its own movement and the change in its own routing table are the only reliable and trustable information. Hence, used data exist on the node's physical movements and the corresponding change in its routing table as the basis of the trace data. The physical movement is measured mainly by distance and velocity. The routing table change is measured mainly by the percentage of changed routes (PCR), the percentage of changes in the sum of hops of all the routes (PCH), and the percentage of newly added routes (Zhang et al., 2003). These measurements are used because of the dynamic nature of mobile networks. The normal profile on the trace data specifies the correlation of physical movements of the node and the changes in the routing table.

Classification rules for PCR and PCH describe normal conditions of the routing table. These rules can be used as normal profiles. Checking an observed trace data record with the profile involves applying the classification rules to the record. Therefore, repeated trials may be needed before a good anomaly detection model is produced.

Detecting Abnormal Activities in Other Layers

Detecting anomalies for other entities of the wireless networks such as MAC protocols, or entities provided by the network (applications and services) follows a similar approach as in the physical layer. For example, the trace data for MAC protocols can contain the following features: for the past *s* seconds, the total number of channel requests, the total number of nodes making the requests, the largest, the mean, and the smallest of all the requests. The class can be the range of the current requests by a node. A classifier on this trace data describes the normal context of a request. An anomaly detection model can then be computed, as a classifier or clusters, from the deviation data. Similarly, at the mobile application layer, the trace data can use the service as the class (Zhang et al., 2003).

WIRELESS INTRUSION DETECTION SYSTEM ARCHITECTURES

This section discusses the proposed models, architectures, and methods to validate the used approaches.

Wireless Intrusion Tracking System

The wireless intrusion tracking system (WITS) deploys the Linksys WRT54G AP, Linux and other open source tools in order to track wireless intruders

in a wireless cell. A WITS is designed to minimize the effect of the attacks against wireless networks. It combines technologies to produce a system that allows real-time tracking of intruders and extensive forensic data gathering (Valli, 2004).

- **Sacrificial access points (SAP):** WITS uses the concept of SAPs, which acts as a wireless honeypot and forensic logging device. The used SAP has conventional wired Ethernet capability. Its functionality is severely limited for deployment as a honeypot device. However, it permits the installation of customized firmware, which allows the reduction of installed facilities used as part of the routing and AP functionality for the WRT54G. The firmware can be upgraded to patch any new vulnerabilities or weaknesses. To be successful, the system must retain large, extensive and multiple log files that contain system statistics and sufficient network related data for forensic reconstruction of any traffic. The used data are data located in honeypot log files, snort data, and data provided by traffic analysis. The data in honeypot logfiles will indicate the level of probing and malicious activity. Traffic analysis provides an extensive analysis of the intruder activity.
- **Tracking the intruder:** Wireless intruders have the ability to be mobile and are not constrained to use predefined channels, which make them difficult to track. Furthermore, wireless attackers can manipulate layer 1 and layer 2 of the OSI model to mask activities and subsequent detection. WITS uses GPS techniques to locate and track intruders within the wireless cell. The resultant GPS data will be stored for later analysis or used by an immediate location process of the attacking device.

Agent-Based IDS for Ad Hoc Wireless Networks

This section introduces a multi-sensor IDS that employs a cooperative detection algorithm. A mobile agent implementation is chosen to support the wireless IDS features such as sensor mobility and intelligent routing of intrusion data throughout the network.

Modular IDS Architecture

The proposed IDS is built on a mobile agent framework. It employs several sensor types that perform specific functions, such as:

- **Network monitoring:** Only certain nodes will have sensor agents for network monitoring, in order to preserve the total computational power and the battery power of mobile hosts.
- **Host monitoring:** Every node on the ad hoc network will be monitored internally by a host-monitoring agent. This includes monitoring system-level and application-level operations.
- **Decision-making:** Every node will decide on the intrusion threat level on a host-level basis. Specific nodes will collect intrusion information and make collective decisions about intrusion level.
- **Reacting:** Every node can react in order to protect the host against detected attacks. Reactions can be predefined at that node.

To minimize power consumption and IDS-related processing time, the IDS must be distributed. A hierarchy of agents can be used to this end. A hierarchy of agents is composed of three agent classes, which are the monitoring agents, decision-making agents, and action agents. Some are present on all mobile hosts, while others are distributed to only selected nodes (Kachirski & Guha, 2003). Cluster heads, for example, are the typical nodes implementing the monitoring agents. The node selection is naturally dependent on the security requirements imposed to the mobile nodes.

Intrusion Response

The nature of an intrusion response for ad hoc networks depends on the intrusion type and the network protocols and applications types. Examples of responses can be:

- Re-initializing communication channels between nodes
- Identifying the compromised nodes and re-organizing the network to preclude the promised nodes
- Notifying the end user and take appropriate action
- Send a re-authentication request to all nodes in the network to prompt the end-users to authenticate themselves (Zhang et al., 2003)

DISTRIBUTED INTRUSION DETECTION

Any *distributed IDS* should enforce mechanisms that support the reliability of its nodes as well as the distributed analysis, integrity, and privacy of exchanged alerts. Several critical problems should be addressed to provide collaborative methods for wireless *distributed intrusion detection*. These problems include the reduction of the volume of alerts; the decrease the complexity of communication and bandwidth requirements; and the management of heterogeneity of formats and protocols.

IDS for PublicWiFi System

The IDS, used by the WIFI systems, bases its detection on network monitoring to produce evidences and share them among all nodes.

The monitor can be thought as an instance of the Ethereal network packet Sniffer. For each captured packet, Ethereal displays a complete view of the packet content and adds some general statistics as a timestamp, frame number, and length in bytes. By looking on the Ethernet level header and focusing on 802.11 frames, source, destination and BSSId addresses; SN; frame type and subtype; and the retry flag are distinguished. Other parameters are added such as counters for transmission retries and for frames received with wrong FCS, and packet transmission time. In this way, a list of events is built and matched, to detect in particular, jamming attacks and channel failures. Since all nodes participate in the detection process, multiple lists are matched to combine the two lists into a single list of events (Aime et al., 2006).

Multi-Layer Integrated Intrusion Detection and Response

Given that there are different kinds of vulnerabilities in mobile network layers, coordinating IDSs within layers is required. The following integration scheme can be investigated:

- If a node detects an intrusion that affects the entire network, it initiates the re-authentication process to exclude the compromised/malicious nodes from the network.
- If a node detects a local intrusion at a higher layer, lower layers are notified.

In this approach, the detection on one layer can be initiated from other layers. To do this, the lower layers need more than one anomaly detection model: one that relies on the data of the current layer and the one that considers information from the upper layer (Zhang et al., 2003).

WIRELESS TOLERANCE AND PREVENTION

Intrusion prevention is considered as an extension of intrusion detection technology, but it is actually another form of access control, like an application layer firewall. Intrusion prevention systems (IPSs) were developed to resolve ambiguities in passive network monitoring by placing detection systems online. Showing a considerable improvement upon firewall technologies, IPSs make access control decisions based on application content, rather than IP address or ports by denying potentially malicious activity. There are advantages and disadvantages to host-based IPS compared with network-based IPS.

Some IPSs can also prevent yet to be discovered attacks, such as those caused by a buffer overflow. Deployed to strengthen wireless security, wireless IPSs monitor radio frequencies in order to detect malicious traffic.

The development and support of intrusion aware survivable applications in wireless networks are key problems in the provision of wireless services.

Significant aspects of intrusion tolerance include: (1) the ability to adapt to changes in environmental and operational conditions for surviving intrusions; (2) the coordination and management of adaptation of changes in service provision; (3) the awareness of resource statuses to respond to attack symptoms effectively; and (4) the management of resource redundancy. The following are two approaches that deploy intrusion tolerance to prevent wireless attacks.

Intrusion Tolerance Based on Multiple Base Stations Redundancy

To provide fault tolerance, this research discusses a redundancy in the form of multiple base stations (BSs). Since an adversary can disallow delivery of sensor data that is routed over only one path to a given BS, a multi-path routing redundancy to improve intrusion tolerance of wireless nodes is introduced (Deng, Han, & Mishra, 2004).

The simplest way to set up multiple paths for each node to multiple BSs is to use a flooding message: each BS broadcasts a unique request message, called REQ. Upon the reception of REQ from a BS, it records the packet sender as its parent node for that BS, and re-broadcasts REQ to its neighbor and child nodes. The node then ignores all copies of the same REQ that it receives later. In this way, the REQ generated by a BS will be able to flood the entire network, even though the network nodes forward that message only once. If one BS broadcast its own REQ, every sensor node will have one path for it. However, this scheme cannot prevent a malicious compromised node from BS spoofing by sending forged REQ. Every node will think that the forged message is generated by the legitimate BS and will forward the forged REQ. To defend against such attack, each BS can authenticate the sent REQ (Deng et al., 2004).

INSENS: Intrusion-Tolerant Routing in Wireless Sensor Networks

INSENS (Deng, Han, & Mishra, 2003, 2005) can be used to prevent DoS attacks, where individual nodes are not allowed to broadcast routing data. Only the BS is allowed to broadcast (Deng et al., 2003). It proposes a BS authentication using a hash function. To prevent DoS/distributed denial of service (DDoS) broadcast attacks, unicast packets must first traverse through the BS. Second, the control routing information has to be authenticated and encrypted by using symmetric cryptography. To address the notion of compromised nodes, redundant multipath routing is built into INSENS to achieve secure routing.

INSENS proceeds through two phases, route discovery and data forwarding. The first phase discovers the sensor network topology, while the second deals with forwarding data from sensor nodes to the BS, and vice versa. Route discovery is performed in three rounds:

- During the first round, the BS floods a request message to all the reachable sensor nodes in the network. The BS broadcasts a request message that is received by all its neighbors. A sensor, receiving a request message for the first time, records the identity of the sender in its neighbor set and then broadcasts a request message. Two mechanisms are used to counter attacks. The first one identifies the request message initiated by the BS using hash. The second mechanism configures sensors with separate pre-shared keys by applying a keyed MAC algorithm to the complete path (Deng et al., 2005).
- During the second round, the sensor nodes send their local information using a feedback message to the BS. After a node has forwarded its request message, it waits a time period before generating a feedback message.
- In the third round, forwarding tables are computed by the BS for each sensor node based on the information received in the second round. Then, it sends them to the respective nodes using a routing update message and waits for a certain period to collect the connectivity information received via feedback messages in order to compute possible paths to each other node. The BS then updates the forwarding tables using entries of the form:

(destination, source, and immediate sender).

> Destination is the node ID of the destination node, source is the node ID of the node that created this data packet, and immediate sender is the ID of the node that just forwarded this packet. Once the data packet is received, a node searches for a matching entry in its forwarding table. If it finds a match, then it forwards the data packet (Deng et al., 2005).

CONCLUSION

We have shown in this chapter that WIDSs have an important role in securing the network by protecting its entities against intrusions and misuse. The protection is performed based on models capable of providing a framework for the description and correlation of attacks. Research works have focused on the development of techniques, approaches, and mechanisms, and WIDS architectures. Architectures include radio frequency fingerprinting, cluster-based detection, mobile devices monitoring, and mobile profile construction. Wireless intrusion prevention and tolerance are also discussed in this chapter; and systems such as INSENS are developed. In addition, we have shown that several challenges need to be addressed to enhance the efficiency of WIDSs.

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KEY TERMS

Access Point (AP): Access point in the base station in a wireless LAN. APs are typically standalone devices that plug into an Ethernet hub or switch. Like a cellular phone system, users can roam around with their mobile devices and be handed off from one AP to the other.

Ad Hoc Networks: Ad hoc networks are local area networks or other small networks, especially ones with wireless or temporary plug-in connections, in which some of the network devices are part of the network only for the duration of a communications session or, in the case of mobile or portable devices, while in some close proximity to the rest of the network.

Intrusion Prevention System (IPS): IPS is the software that prevents an attack on a network or computer system. An IPS is a significant step beyond an intrusion detection system (IDS), because it stops the attack from damaging or retrieving data. Whereas, an IDS passively monitors traffic by sniffing packets off a switch port, an IPS resides inline like a firewall, intercepting and forwarding packets. It can thus block attacks in real time.

Intrusion Tolerance: Intrusion tolerance is the ability to continue delivering a service when an intrusion occurs.

Wireless Attack: A wireless attack is a malicious action against wireless system information or wireless networks; examples can be denial of service attacks, penetration, and sabotage.

Wireless Intrusion Detection System (WIDS): The WIDS is the software that detects an attack on a wireless network or wireless system. A network IDS (NIDS) is designed to support multiple hosts, whereas a host IDS (HIDS) is set up to detect illegal actions within the host. Most

IDS programs typically use signatures of known cracker attempts to signal an alert. Others look for deviations of the normal routine as indications of an attack. Intrusion detection is very tricky.

Wireless Sensors Networks (WSN): WSN is a network of RF transceivers, sensors, machine controllers, microcontrollers, and user interface devices with at least two nodes communicating by means of wireless transmissions.

Wireless Traffic Anomaly: Wireless traffic anomaly is a deviation from the normal wireless traffic pattern. An intrusion detection system (IDS) may look for unusual traffic activities. Wireless traffic anomalies can be used to identify unknown attacks and DoS floods.

Wireless Vulnerability: Wireless vulnerability is a security exposure in wireless components. Before the Internet became mainstream and exposed every organization in the world to every attacker on the planet, vulnerabilities surely existed, but were not as often exploited.

Chapter VII
Peer-to-Peer (P2P) Network Security:
Firewall Issues

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INTRODUCTION

A lot of networks today are behind firewalls. In peer-to-peer (P2P) networking, firewall-protected peers may have to communicate with peers outside the firewall. This chapter shows how to design P2P systems to work with different kinds of firewalls within the object-oriented action systems framework by combining formal and informal methods. We present our approach via a case study of extending a Gnutella-like P2P system (Yan & Sere, 2003) to provide connectivity through firewalls.

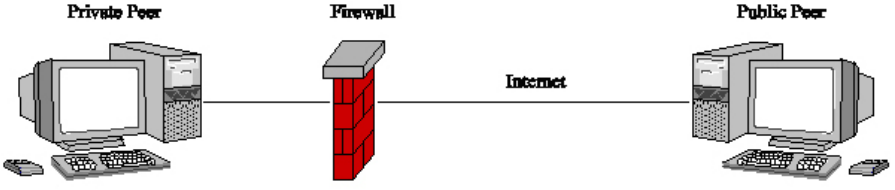
PROBLEM DEFINITION

As firewalls have various topologies (single, double, nested, etc.) and various security policies (packet filtering, one-way-only, port limiting, etc.), our problem has multiple faces and applications have multitude requirements. A general solution that fits all situations seems to be infeasible in this case. Thus we define the problem as shown in Figure 1: How to provide connectivity between private peers and public peers through a single firewall?

We select the object-oriented action systems framework with Unified Modeling Language (UML) diagrams as the foundation to work on. In this way, we can address our problem in a unified framework with benefits from both formal and informal methods.

Action systems is a state based formalism. It is derived from the guarded command language of Dijkstra (1976) and defined using *weakest precondition* predicate transformers. An action, or guarded command, is the basic building block

Figure 1. Problem definition



in the formalism. An action system is an iterative composition of actions. The action systems framework is used as a specification language and for the correct development of distributed systems.

Object-oriented (OO)-action system is an extension to the action system framework with OO support. An OO-action system consists of a finite set of classes, each class specifying the behavior of objects that are dynamically created and executed in parallel. The formal nature of OO-action systems makes it a good tool to build reliable and robust systems. Meanwhile, the OO aspect of OO-action systems helps to build systems in an extendable way, which will generally ease and accelerate the design and implementation of new services or functionalities. Furthermore, the final set of classes in the OO-action system specification is easy to be implemented in popular OO languages like Java, C++ or C#.

In this chapter, however, we skip the details of semantics of action systems (Back & Sere, 1996) and its OO extension (Bonsangue, Kok, & Sere, 1998).

GNUTELLA NETWORK

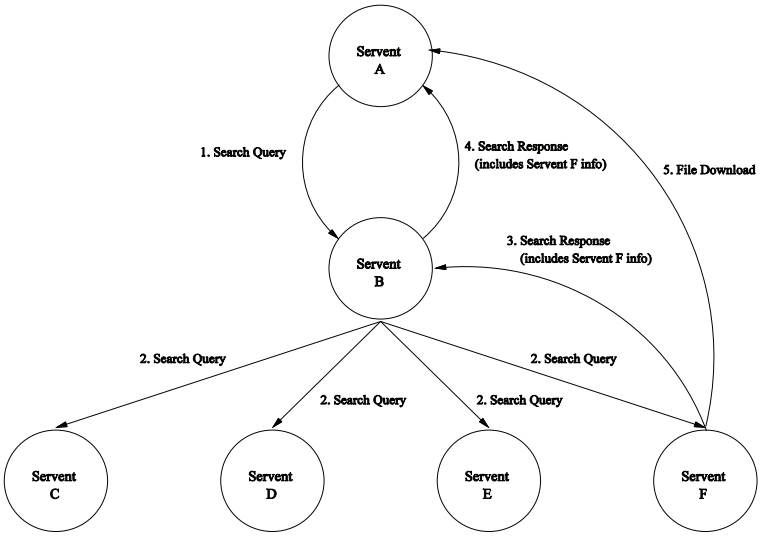
Gnutella (Ivkovic, 2001) is a decentralized P2P file-sharing model that enables file sharing without using servers. To share files using the Gnutella model, a user starts with a networked computer A with a Gnutella *servent*, which works both as a server and a client. Computer A will connect to another Gnutella-networked computer B and then announce that it is *alive* to computer B. B will in turn announce to all its neighbors C, D, E, and F that A is alive. Those computers will recursively continue this pattern and announce to their neighbors that computer A is alive. Once computer A has announced that it is alive to the rest of the members of the P2P network, it can then search the contents of the shared directories of the P2P network.

Search requests are transmitted over the Gnutella network in a decentralized manner. One computer sends a search request to its neighbors, which in turn pass that request along to their neighbors, and so on. Figure 2 illustrates this model. The search request from computer A will be transmitted to all members of the P2P network, starting with computer B, then to C, D, E, F, which will in turn send the request to their neighbors, and so forth. If one of the computers in the P2P network, for example, computer F, has a match, it transmits the file information (name, location, etc.) back through all the computers in the pathway towards A (via computer B in this case). Computer A will then be able to open a direct connection with computer F and will be able to download that file directly from computer F.

UNIDIRECTIONAL FIREWALLS

Most corporate networks today are configured to allow outbound connections (from the firewall protected network to Internet), but deny inbound connections (from Internet to the firewall protected network) as illustrated in Figure 3.

Figure 2. Gnutella peer-to-peer model



These corporate firewalls examine the packets of information sent at the transport level to determine whether a particular packet should be blocked. Each packet is either forwarded or blocked based on a set of rules defined by the firewall administrator. With packet-filtering rules, firewalls can easily track the direction in which a TCP connection is initiated. The first packets of the TCP three-way handshake are uniquely identified by the flags they contain, and firewall rules can use this information to ensure that certain connections are initiated in only one direction. A common configuration for these firewalls is to allow all connections initiated by computers inside the firewall, and restrict all connections from computers outside the firewall. For example, firewall rules might specify that users can browse from their computers to a web server on Internet, but an outside user on Internet cannot browse to the protected user's computer.

In order to traverse this kind of firewall, we introduce a *Push* descriptor and routing rules for servents: Once a servent receives a QueryHit descriptor, it may initiate a direct download, but it is impossible to establish the direct connection if the servent is behind a firewall that does not permit incoming connections to its Gnutella port. If this direct connection cannot be established, the servent attempting the file download may request that the servent sharing the file *push* the file instead. That is, A servent may send a Push descriptor if it receives a QueryHit descriptor from a servent that does not support incoming connections.

Intuitively, Push descriptors may only be sent along the same path that carried the incoming QueryHit descriptors as illustrated in Figure 4. A servent that receives a Push descriptor with *ServentID* = *n*, but has not seen a QueryHit descriptor with *ServentID* = *n* should remove the Push descriptor from the network. This ensures that only those servents that routed the QueryHit descriptors will see the Push descriptor.

We extend our original system specification (Yan & Sere, 2003) to adopt unidirectional firewalls by adding a Push router *Rf*, which is a new action system modeling Push routing rules as shown in Table 1. We compose it with the previous two action systems (Yan & Sere, 2003) *Rc* modeling Ping-Pong routing rules and *Rl* modeling Query-QueryHit routing rules together, to derive a new specification of router

$R = |[\ Rc \ // \ Rl \ // \ Rf \ ]|$

Figure 3. Unidirectional firewall

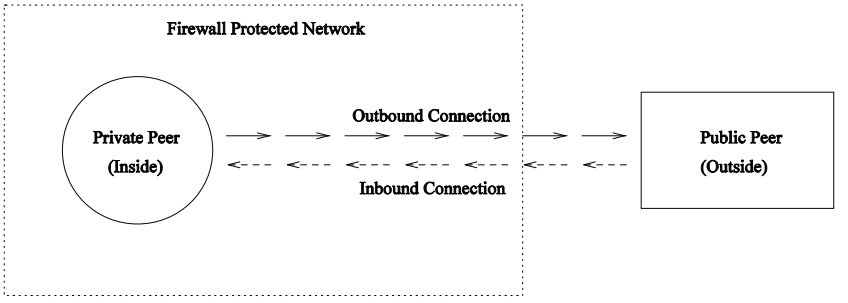
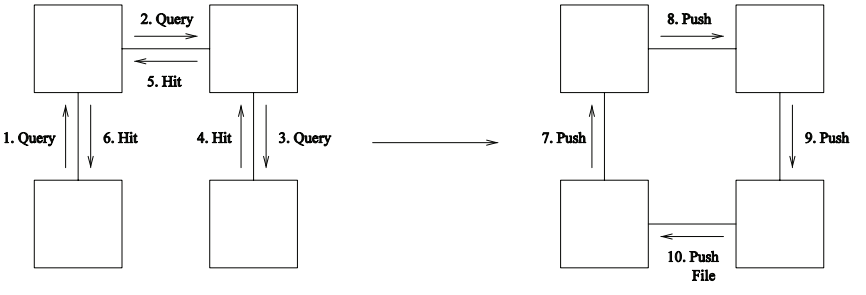


Figure 4. Push routing



where on the higher level, we have components of a new router

{<*Router, R*>, <*PingPongRouter, Rc*>, <*QueryRouter, Rl*>, <*PushRouter, Rf*>}.

A servent can request a file push by routing a Push request back to the servent that sent the QueryHit descriptor describing the target file. The servent that is the target of the Push request should, upon receipt of the Push descriptor, attempt to establish a new TCP/IP connection to the requesting servent. As specified in the refined file repository in Table 2, when the direct connection is established, the firewalled servent should immediately send a HTTP GIV request with *requestIP, filename* and *destinationIP* information, where requestIP and destinationIP are IP address information of the firewalled servent and the target servent for the Push request, and filename is the requested file information. In this way, the initial TCP/IP connection becomes an outbound one, which is allowed by unidirectional firewalls. Receiving the HTTP GIV request, the target servent should extract the requestIP and filename information, and then construct an HTTP GET request with the above information. After that, the file download process is identical to the normal file download process without firewalls. We summarize the sequence of a Push session in Figure 5.

PORT-BLOCKING FIREWALLS

In corporate networks, other kinds of common firewalls are port-blocking firewalls, which usually do not grant long-time and trusted privileges to ports and protocols other than port 80 and

Table 1. Specification of push router

```
Rf = |[ attr serventDB := null; cKeyword := null;
        filename := null; target := null;
        pushTarget := null
     obj receivedMsg : Msg; newMsg : Msg;
        f : FileRepository
     meth SendPush( ) =
          (newMsg := new(Msg(Push));
           newMsg.info.requestIP := ThisIP;
           newMsg.info.filename :=
            receivedMsg.info.filename;
           newMsg.info.destinationIP :=
            receivedMsg.info.IP;
           OutgoingMessage := newMsg);
         ReceiveMsg( ) = receivedMsg :=
           IncomingMessage;
         ForwardMsg(m) = (m.TTL > 0 →
           m.Transmit( );
           OutgoingMessage := m)
     do
        true→
         ReceiveMsg( );
         if receivedMsg.type = QueryHit→
            serventDB := serventDB ∪
            receivedMsg.serventID;
           if receivedMsg.info.keyword =
            cKeyword→
              target := receivedMsg.info.filename
              @receivedMsg.info.IP;
              if f.firewall→
                 SendPush( )
              fi
              cKeyword := null
           [] receivedMsg.info.keyword≠
              cKeyword ∧
              receivedMsg.descriptorID ∈
              descriptorDB→
                        ForwardMsg(receivedMsg)
```

Table 1. continued

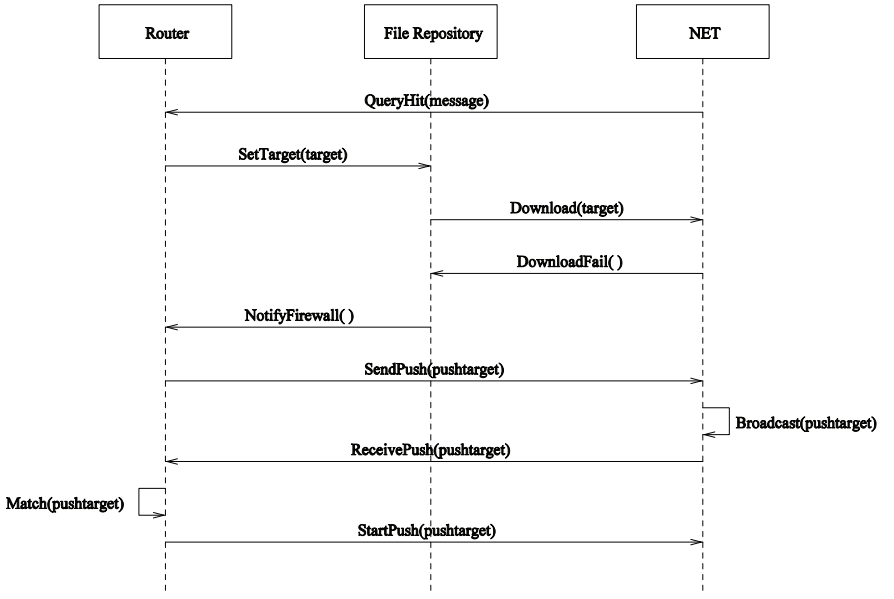
```
     fi
          [] receivedMsg.type = Push→
              if receivedMsg.info.destinationIP =
               ThisIP→
                PushTarget :=
                 receivedMsg.info.requestIP®
                 receivedMsg.info.filename@
                 receivedMsg.info.destinationIP
              [] receivedMsg.info.destinationIP≠
               ThisIP ∧
               receivedMsg.serventID ∈
               serventDB→
                ForwardMsg(receivedMsg)
              fi
          fi
     od
  ]|
```

HTTP/HTTPS. For example, port 21 (standard FTP access) and port 23 (standard Telnet access) are usually blocked and applications are denied network traffic through these ports. In this case, HTTP (port 80) has become the only entry mechanism to the corporate network. Using HTTP protocol, for a servent to communicate with another servent through port-blocking firewalls, the servent has to *pretend* that it is an HTTP server, serving WWW documents. In other words, it is going to mimick an *httpd* program.

When it is impossible to establish an IP connection through a firewall, two servents that need to talk directly to each other solve this problem by having SOCKS support built into them, and having SOCKS proxy running on both sides. As illustrated in Figure 6, it builds an HTTP tunnel between the two servents.

After initializtion, the SOCKS proxy creates a *ProxySocket* and starts accepting connections on the Gnutella port. All the information to be sent by the attempting servent is formatted as a URL message (using the GET method of HTTP) and an *URLConnection* via HTTP protocol (port 80) is

Figure 5. Sequence diagram of a push session



made. On the other side, the target servent accepts the request and a connection is established with the attempting servent (actually with the SOCKS proxy in the target servent). The SOCKS proxy in the target servent can read the information sent by the attempting servent and write back to it. In this way, transactions between two servents are enabled.

We extend our original system specification (Yan & Sere, 2003) to adopt port-blocking firewalls by adding a new layer to the architecture of servent in Figure 7. This layer will act as a tunnel between servent and Internet.

As specified in Table 3, after receiving messages from the attempting servent and encoding them into HTTP format, the SOCKS proxy sends the messages to the Internet via port 80. In the reverse way, the SOCKS proxy keeps receiving messages from HTTP port and decoding them into original format. With this additional layer, our system can traverse port-blocking firewalls without any changes in its core parts. We summarize the sequence of a SOCKS proxy session in Figure 8.

CONCLUSION

The corporate firewall is a double-edged sword. It helps prevent unauthorized access to the corporate Web, but may disable access for legitimate P2P applications. There have been protocols such as Point-to-Point Tunneling Protocol (PPTP) (Hamzeh et al., 1999), Universal Plug and Play (UPNP) (Microsoft, 2000), Realm Specific IP (RSIP) (Borella & Montenegro, 2000) and Middlebox protocol (Reynolds & Ghosal, 2002) to address the firewall problems in P2P networking. A recent protocol, JXTA (Gong, 2001) from Sun has provided an alternative solution to the firewall problem by adding a publicly addressable node, called *rendezvous server*, which a firewalled peer can already talk to. The scheme is that peers interact mostly with their neighbors who are on the same side of the firewall as they are and one or a small number of designated peers can bridge between peers on the different sides of the firewall. But the problem posed by firewalls still remains when configuring the firewalls to allow traffic through these bridge peers.

We have specified a Gnutella-like P2P system within the OO-action systems framework by combining UML diagrams. In this chapter, we have

Table 2. Specification of file repository

```
F = |[ attr firewall* := false; fileDB := FileDB;
        cFileDB; filename := null; target := null;
        pushTarget := null
     meth SetTarget(t) = (target := t);
          PushTarget(t) = (pushTarget := t);
          Has(key) = ({key} c dom(fileDB));
          Find(key) = (filename := file ^
            {file} c ran({key} ◀ fileDB))
     do
        target≠ null→
          cFileDB := fileDB;
          HTTP_GET(target);
          target := null;
          Refresh(fileDB);
          if fileDB = cFileDB→
             firewall := true
          [] fileDB≠ cFileDB→
             firewall := false
          fi
       [] pushTarget≠ null→
          HTTP_GIV(pushTarget);
          pushTarget := null;
          Refresh(fileDB)
     od
  ]|
```

Figure 7. Refined architecture of servent

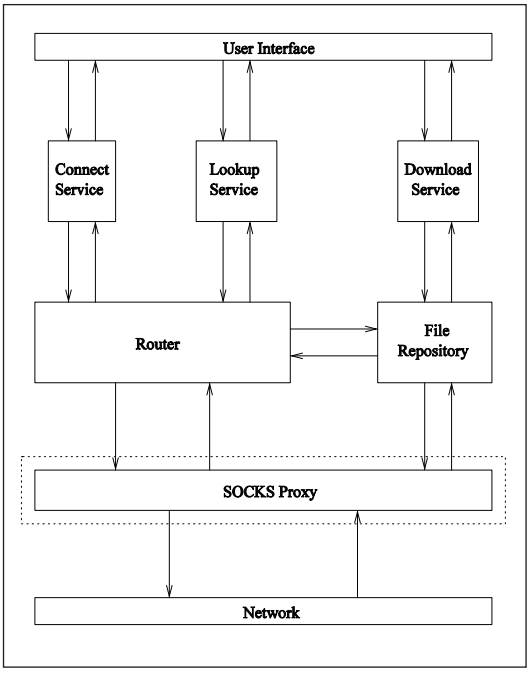


Figure 6. Firewall architecture and extendable socket

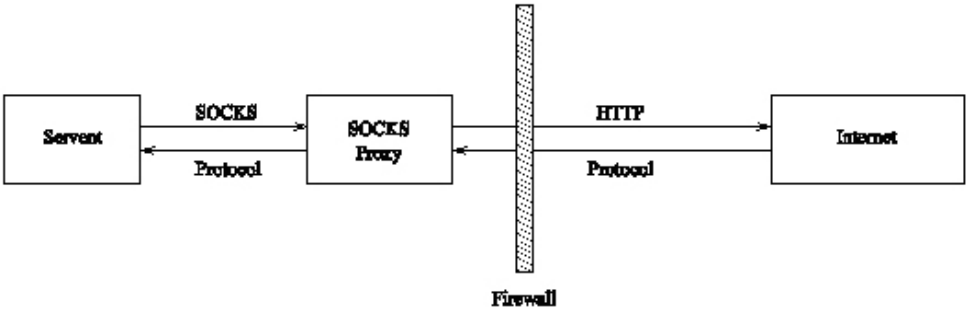


Table 3. Specification of SOCKS proxy

```
S = |[ attr listenPort := GnutellaPort;
          DestinationPort := 80
       obj ProxySocket : Socket;
          HTTPSocket : Socket;
          imsg : Msg; omsg : Msg
       init ProxySocket = new(Socket(listenPort));
          HTTPSocket =
            new(Socket(destinationPort))
       do
           IncomingRequest ≠ null→
             imsg := EncodeSOCK(DecodeHTTP
               (HTTPSocket.Read( )));
             IncomingMessage :=
               ProxySocket.Write(imsg)
         [] OutgoingRequest≠ null→
             omsg := EncodeHTTP(DecodeSOCK
               (ProxySocket.Read( )));
             OutgoingMessage :=
               HTTPSocket.Write(omsg)
       od
    ]|
```

presented our solution to traverse firewalls for P2P systems. We have extended a Gnutella-style P2P system to adopt unidirectional firewalls and port-blocking firewalls using OO-action systems. During the extending work, our experiences show that the OO aspect of OO-action systems helps to build systems with a reusable, composable, and extendable architecture. The modular architecture of our system makes it easy to incorporate new services and functionalities without great changes to its original design.

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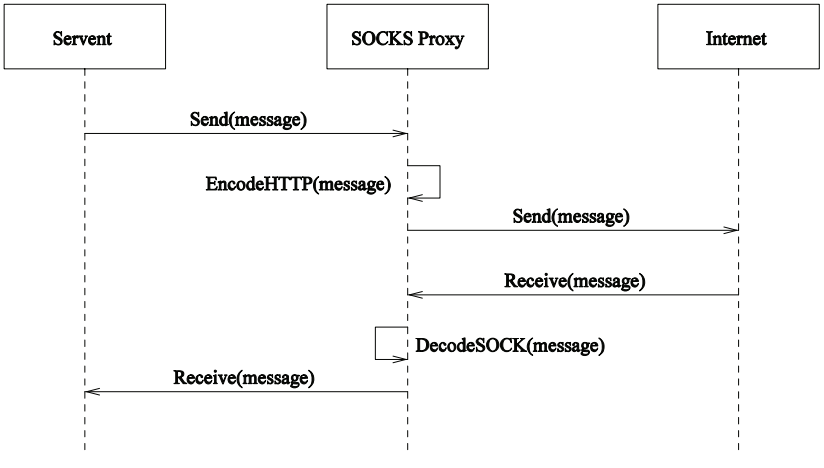
Figure 8. Sequence diagram of a SOCKS proxy session



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KEY TERMS

Action System: An action system is a notation for writing programs, due to Ralph Back. An action system is a collection of actions. It is executed by repeatedly choosing an action to execute. If it is the case that no action is able to be executed, then execution of the action system stops.

Firewall: A firewall is a piece of hardware and/or software which functions in a networked environment to prevent some communications forbidden by the security policy, analogous to the function of firewalls in building construction.

Peer-to-Peer (P2P): A peer-to-peer (P2P) computer network is a network that relies primarily on the computing power and bandwidth of the participants in the network rather than concentrating it in a relatively low number of servers. P2P networks are typically used for connecting nodes via largely ad hoc connections.

Chapter VIII
Identity Management for Wireless Service Access

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ABSTRACT

Ubiquitous access and pervasive computing concept is almost intrinsically tied to wireless communications. Emerging next-generation wireless networks enable innovative service access in every situation. Apart from many remote services, proximity services will also be widely available. People currently rely on numerous forms of identities to access these services. The inconvenience of possessing and using these identities creates significant security vulnerability, especially from network and device point of view in wireless service access. After explaining the current identity solutions scenarios, the chapter illustrates the on-going efforts by various organizations, the requirements and frameworks to develop an innovative, easy-to-use identity management mechanism to access the future diverse service worlds. The chapter also conveys various possibilities, challenges, and research questions evolving in these areas.

INTRODUCTION

Nowadays people are increasingly connected through wireless networks from public places to their office/home areas. The deployment of packet-based mobile networks has provided mobile users with the capability to access data services in every situation. The next-generation wireless network is expected to integrate various radio systems including third generation (3G), wireless LANs (WLANs), fourth generation (4G), and others. One motivation of this network is the pervasive computing abilities, which provide automatic handovers for any moving computing devices in a globally networked environment. Fast vertical handover is considered important for managing continued access to different types of network resources in next generation networks (Li et al., 2005). Such networks will provide ubiquitous service access taking the advantages of each of these forms of wireless communications. Service intake will be increased significantly through the availability and reach of innovative and easy-to-use services. Apart from the remote service access (Web services), the introduction of near field communication (NFC) in use with a mobile phone can enable many new proximity services.

User identity solutions and its hassle-free management will play a vital role in the future ubiquitous service access. Current identity solutions can no longer cope with the increasing expectations of both users and service providers in terms of their usability and manageability. Mobile and Internet service providers are increasingly facing the same identity management challenges as services in both domains continue to flourish. Real-time data communication capabilities of mobile networks will multiply the remote service accesses through mobile networks, if efficient identity management and security is ensured over the wireless access. Personalization through customized user profiles based on their preferences will become an important factor for success of future wireless service access. In more advanced service scenarios, open identity management architecture enables the use of standard user profile attributes, like age and gender, and authorizations for service, such as location, to bring a richer user experience. Users, network operators, and service providers can make use of an open standard technology for identity management to meet their own specific requirements through customizations. There is clearly a need for such a standard for identity management that can be applied to all ubiquitous service access scenarios. As user needs are at the center in the service world from business perspective, identity management mechanism should be user-centric.

The impressive capabilities and reach of emerging next-generation networks, the abundance of services, and on-going development in user device require proper address to the user identity management issues which have yet met the stakeholders' expectations. The main goal of this chapter is to discuss these concerns. The second section discusses the background of identity management. In the third section, requirements and framework of identity management mechanism for wireless service access are given mentioning the current efforts by various organizations. Security issues are also a part of this mechanism. The fourth section provides the future trends. The chapter concludes with the summary of all discussions.

BACKGROUND

In a broadest sense, identity management encompasses definitions and life-cycle management for user identities and profiles, as well as environments for exchanging and validating such information. A service provider issues identity to its users. Identity life-cycle management comprises establish/re-establishment of identity, description of identity attributes, and at the end revocation of identity. Attributes are a set of characteristics of an identity that are required by the service providers to identify a user during service interactions. User authenticates to the service providers as real owner of the identity for accessing services. Authentication is a key aspect of trust-based identity attribution, providing a codified assurance of the identity of one entity to another.

Next-generation wireless network includes state-of-the-art intelligent core network and various wireless access networks. It is expected to offer sufficient capacity, quality of service (QoS), and interoperability for seamless service access remotely. Currently the network and thereby the remote service access are often granted through numerous user identification and authentication mechanisms, such as, usernames/passwords/PIN codes/certificates. Users have to register prior to first usage and publish private information, often more than what is strictly necessary for service access. It hampers user's privacy. There is a growing consensus among the legislators across the world that individual's rights of privacy and the protection of personal data is equally applicable in the context of the Information Society as it is in the off-line world. To address this issue, a user-centric identity management framework is expected where users having complete control over the identity information transmission.

Some services happen in the proximity of users at local access points. These services are accessed through physical interactions with physical cards or devices, for example, payment and admittance. The use of NFC with mobile phones to transfer user information from one device to another boosts the intake of proximity services. The user personal

device is often used to store his/her identity information. To protect unauthorized service access, users also need to be authenticated before accessing such devices. It is evident that a user is burdened with too many identities to access many remote and proximity services. An integrated approach is required to manage all those identities to access all these services.

Wireless service access results in more complexity to manage identities prior to accessing the services. Besides device authentications, users need to authenticate themselves before accessing the wireless networks. In addition to this, because of the size limitations, mobile devices are equipped with smaller screens and limited data entry capabilities using small keypads. For wireless services to succeed, it is critical that the mobile users are able to get convenient and immediate access to the information and services they need without going through long menus and having to enter various usernames and passwords.

In the future, one of the key issues of identity management in the wireless domain will be who the identity providers will be to the users and who will own/manage the subscriber identity module (SIM/USIM). It is because, currently, almost every service provider is also an identity provider for users to access that specific service. SIM card is in fact a smart card with processing and information storage capabilities. With the development of powerful, sophisticated as well as secure smart cards, it is now considered as the storage place for user's identity information. In current cellular models, the operator provides not only the wireless access but also owns and manages SIM/USIM. In this case, the user has little control over his/her identity. A user is having a SIM/USIM as his/her identity but is not allowed to modify or update it so that he/she cannot subscribe to new wireless providers or to whatever service providers he/she likes. A collaborative operator model has been thought where such identity module belongs to the user (Kuroda, Yoshida, Ono, Kiyomoto, & Tanaka, 2004, pp. 165-166). A third party can provide the infrastructure to manage such identity. This approach leads towards user-centric identity management and provides the user with flexibility in choosing wireless providers.

In general, common identity deployment architectures can be broadly classified into three types: Silo, Walled Garden, and Federation (Altmann & Sampath, 2006, p. 496). Current identity management in the service world is mostly silo-based. Silo is a simple architecture, which requires each service provider to maintain a unique ID for each user. This approach is simpler from a service provider's point of view but it is not only laborious but also problematic for the user. Moreover, it results in a huge waste of resources due to the possession of redundant identity information in the service world. As studies show, users who register with several service providers routinely forget their passwords for less frequently used accounts. This has a significant financial effect. On average, $45 is spent on password reset each time a user forgets a password (Altmann & Sampath, 2006, p. 496). Walled Garden is a centralized identity management approach where all service providers can typically rely on one singe identity provider to manage the user's identity. The user is benefited through managing only a single set of credentials. Its inherent weakness is, once the significant barrier of protection is compromised, a malicious user enjoys unbridled access to all resources. Lastly, in identity federation management a group of service providers forms a federation. Here, each service provider recognizes the identifiers of other service providers and thereby, consider a user who has been authenticated by another service provider to be authenticated as well. However, the real distinction between Walled Garden and Federation approach is that here service providers have their own unique identifiers and credentials. Though this approach is widely accepted considering the heterogeneity of service providers, many possible service interaction scenarios and the requirements of several levels of security make such a system far more complex.

IDENTITY MANAGEMENT FOR WIRELESS SERVICE ACCESS

Designing an identity management mechanism to access both remote and proximity services, without

using numerous inconvenient identity solutions, is expected to be the main focus in the identity management for service access over wireless networks. This section also considers the selection of a user identity storage place, the role of identity provider, and various other requirements to develop such a mechanism from a wireless service access point of view.

Requirements of Identity Management Systems

Identity management system should be user-centric. It means such a system should reveal information identifying a user with user's consent. Security is one of the most important concerns of this system. The system should protect the user against deception, verifying the identity of any parties who ask for information to ensure that it goes to the right place. In the user-centric approach, the user will decide and control the extent of identifying information to be transmitted. The system must disclose the least identifying information possible. By following these practices, the least possible damage can be ensured in the event of a breach. These are some of the requirements to design a user-centric identity management system in The Laws of Identity (Cameron, 2005).

Identity management system requires an integrated and often complex infrastructure where all involved parties must be trusted for specific purposes depending on their role. Since there are costs associated with establishing trust, it will be an advantage to have identity management models with simple trust requirements (Jøsang, Fabre, Hay, Dalziel, & Pope, 2005). Success of an identity management system depends upon the ability to interoperate across a trusted network of businesses, partners, and services regardless of the platform, programming language, or application with which they are interacting. It should handle user identities for both remote (Web) and proximity service access. Above all, such a system should be user friendly.

Identity Management Solutions and Controversies

Various institutes and industries are working to develop the required identity management solutions. SXIP ("The SXIP 2.0 Overview," n.d.). identity has designed a solution to address the Internet-scalable and user-centric identity architecture. It provides user identification, authentication and Internet form fill solutions using Web interfaces for storing user identity, attribute profiles, and facilitating automatic exchange of identity data over the Internet. Windows CardSpace uses various virtual cards (mimic physical cards) issued by the identity providers for user identifications and authentications, each retrieving identity data from an identity provider in a secure manner (Chowdhury & Noll, 2007). In the Liberty Alliance Project (Miller et al., 2004), members are working to build open standard-based specifications for federated identity and interoperability in multiple federations, thereby fostering the usage of identity-based Web services. Within this, they are focusing on end-user privacy and confidentiality issues and solutions against identity theft. But these efforts are mainly focusing on identity management in the Internet domain.

Besides working for identity handling in a Web domain, Liberty Alliance (Miller et al., 2004) also provides solutions in identity management for mobile operators. It proposes single sign-on (SSO) to relieve the users from managing many usernames/passwords and for fast access to the resources. But in SSO, if a malicious attacker secures one of the user's accounts, he/she will enjoy an unbridled access to data pertaining not only to that account but also across all her accounts spread across domains. Therefore, some research approaches do not encourage such SSOs (Altmann & Sampath, 2006, p. 500). However, a current version of liberty, Shibboleth, reduces such risk by providing an attribute-based authorization system. But in wireless service access, especially for mobile devices seamless service sign-on solutions and one-click access to personalized services are key issues for successful identity management.

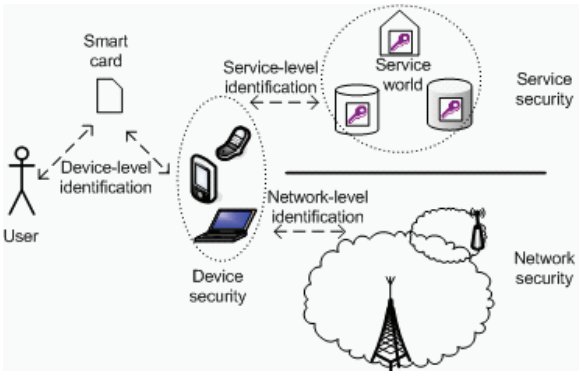
Apart from possessing numerous usernames/passwords/PIN codes for remote (Web) service access, the user is also carrying many physical identities for proximity service access. These include credit card, bank card, home/office access cards, and so forth. Many researchers working in these areas are proposing the smart cards, like SIM/USIM currently used in mobile phones, as the secure storage place for the user's identity information because it can be revoked, users nowadays can rarely be found without a mobile phone and there are possibilities of security enhancements. Custom made SIMs/USIMs having enough computational power and storage space can be used to manage users' identification information and multi-factor authentication mechanisms. Gemalto, a company providing digital security, is involved in developing sophisticated smart cards (e.g., SIM/USIM) based online or off-line identity management with associated software, middleware, and server-based solutions. NXP, a semiconductor company (formerly a division of Philips), is also offering identification products in areas like government, banking, access control, and so forth using secure innovative contactless smart cards and chips. Credit card companies are running various trials for providing user's payment identity handling solutions using mobile phones and NFC technology. *Tap N Go* is the name of a contactless payment trial powered by MasterCard *PayPass* (2007) in the U.S. started in 2006. In the same year, Visa completed contactless-based mobile pilots in Malaysia and the United States, using NFC-enabled phones, complementing existing programs in Japan and Korea. In February 2007, Visa International and SK Telecom of South Korea announced the world's first contactless payment application on a universal SIM card which is personalized over-the-air based on Visa's recently introduced mobile platform ("Visa's mobile platform initiative," 2007).

Identity providers issue identities to each user. They have a very important central role in the identity management business. The identity provider manages users' identities and their access rights to various services securely. It provides the authentication and authorization services to the users. Who can be the identity providers in future identity management systems, is a debatable issue. Liberty Alliance (Miller et al., 2004) believes that mobile operators are in a good position to become the most favored identity providers, because they possess valuable static and dynamic user information which can be transmitted to third parties in a controlled manner through open standard Web service interface. Mobile operators also have the ability to seamlessly authenticate users with the phone number on behalf of the service providers (SP). Many contradict such roles of mobile operators. Instead a more trusted third party, like financial institutes and governments are also well positioned to become preferred identity providers. They might provide identity services for their specific market and services that need stronger user identities. When a user wants to subscribe to a new wireless network, he/she asks the third party identity provider to add new identification data into his/her phone. In such a situation, it is possible that a third party can even manage SIM/USIM, which is currently done by cellular operators. It is expected that the next-generation wireless network will have such flexibility.

Components of User Identities

Identity management in wireless service access needs to address device-level security, network-level security, and service-level security (Kuroda et al., 2004, p. 169). Therefore, the over-all user identity comprises device, network, and service identities. The user's device is divided into two components, a personal smart card (e.g., SIM/USIM) and mobile devices with wireless access capabilities. The smart card includes user identification data that contains user's public or shared-secret keys, certificates for network operators, and service providers. The card and the device need to be mutually authenticated in the initial setup phase because both devices have built no relationship of trust to exchange security information from the very beginning. Afterwards, the user identifies him/herself to the card, since it stores sensitive personal information, which is used for network- and service-level authentication. The user can identify through PIN, password, or biometrics. After these authentication procedures,

Figure 1. User identifications to ensure device-, network-, and service-level security



the card delegates user identity information to the mobile device to authenticate wireless access and thereby, service access. The user expects to use services without being concerned about the individual characteristics of each wireless access. Network-level authentication verifies that the user is a subscriber and has wireless access to the right network. Service-level authentication verifies that the user is a subscribed user to the right services. In each case, service or network providers and user device mutually authenticate each other. Figure 1 depicts the overview of device-, service-, and network-level identifications to ensure the security of user-device, network, and services for wireless service access.

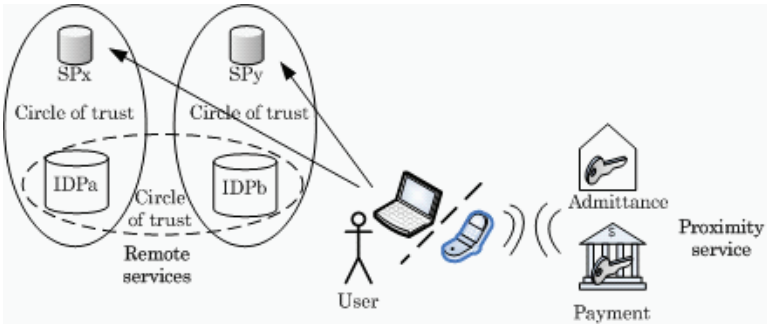
Integrated Identity Management Mechanism

Every human being is playing numerous roles in life to live. To organize the user identities in a more structured way, all user identities can be broadly categorized into three areas based on the roles he/she exercises in real life (Chowdhury & Noll, 2006). These are personal identity (PID), corporate identity (CID), and social identity (SID). PIDs can be used to identify a user in his/her very personal and commercial service interactions. CIDs and SIDs can be used in professional and social, interpersonal interactions respectively. For example, PIDs include bank/credit card, home/office access card/code, and so forth. According to Dick Hardt (keynote speech at OSCON 2005 conference), founder and CEO of SXIP Identity, individual's interests, fondness, preferences, or tastes are also part of his/her identity. These roles can be dealt with by user's SIDs. Some of these identities are having very sensitive user information therefore very strict authentication requirements have to be met. Some others require less secure infrastructure as they possess not so sensitive user information.

Considering all these aspects, instead of storing user's vast identity information into a single place (a user device), these can be distributed into two places. The less sensitive user identity information, especially his/her SIDs can be stored in a secure network identity space. The most sensitive identity information like user's PIDs will be stored in user's personal device. The mobile phone (more correctly the SIM card) has been proposed as the user's personal device (Chowdhury & Noll, 2006). When the user subscribes to the identity services, the identity provider (IDP) issues a certificate to him/her. It will be stored in the device. At the same time, a secure identity space in the network will be allocated for the user too. The device identifies and authenticates the user to access his/her network identity space. When the user authenticates to the device and the network, he/she can also gain access to the network identity space (if it requires, an optional password can also protect such access). The user device holds the most sensitive user identity information. Depending on the security requirements of the services, the possession-based authentication (e.g., having a personal device) can be enhanced by a knowledge factor (e.g., PIN code). An additional knowledge-based authentication mechanism can be used here to grant access to sensitive PIDs stored in the device. This is how user identities can be stored in a distributed manner and multi-factor authentication mechanisms can protect the security of user's identities.

In future service access scenarios, the user expects a hassle-free use of identities. In this regard an approach is expected to integrate all user's identities to access every remote and proximity services into a single mechanism. The distributed identity infrastructure just being described can also

Figure 2. A generic diagram for integrated identity mechanism and service access



provide an integrated mechanism to handle the use of identities for every possible service access over the wireless network. For example, by using public key infrastructure (PKI) built in SIM card user can access services of banks remotely; with the NFC capable mobile phone user, can access home premises transferring the stored admittance key from user device. This is how a proximity service access can also be handled. Figure 2 shows a generic diagram for integrated identity mechanism to handle remote and proximity service access.

In a significant move towards providing secure ubiquitous digital credentials management; the banking industry of Norway with a partnership of a mobile operator initiated PKI-based BankID (Cybertrust Case Studies Library, 2005) for identification and signing agreement on the move. BankID for mobile phones will initially be used in four areas: (1) logging on to Internet banks, (2) mobile banking, (3) electronic service for business and the public sector, and (4) account-based payment service for the Internet and mobiles.

Security Infrastructure in Identity Management Systems

The wireless network along with the user device (mobile phone) can serve as the underlying secure infrastructure for exchanging user identity information and authentication messages. The next generation network will integrate 3G and WLAN to offer subscribers high-speed wireless data services as well as ubiquitous connectivity (Siddiqui et al., 2005). Users are expected to access countless services seamlessly over the wireless network. Hence, secure identity information handling is a crucial issue in wireless service access. In the mobile domain, the security of 3G mobile systems has already been strengthened by introducing longer cipher keys; mutual (network, user) authentication; signaling and data traffic integrity; and the extension of ciphering back into the network (Boman, Horn, Howard, & Niemi, 2002, pp. 192-200). WLAN security has been improved significantly with the adoption of IEEE 802.11i. It was created in response to several serious weaknesses researchers had found in the previous system, wired equivalent privacy (WEP). There have been discussions to accomodate both 3G and WLAN security frameworks on the IP layer or based on 3rd Generation Partnership Project (3GPP), but the resulting solution does not offer fast vertical handover which is critical for session continuity (Kuroda et al., 2004, p. 166). EAP-TLS and EAP-AKA have been proposed to provide strong end-to-end security and authentication to the user in such integrated network environment (Kambourakis, Rouskas, & Gritzalis, 2004, pp. 287-296). Due to the various weaknesses of Bluetooth/Infrared communications, NFC is considered as the secure technology to transfer user identity information between a user's mobile phone and the devices at service points. Its short range should mitigate the risk of eavesdropping by other reader devices. It is practically impossible to do man-in-the-middle attack on NFC link (Haselsteiner

& Breitfuss, 2006). Moreover, a secure channel can be established using cryptographic protocol between the two NFC devices.

Identity management and associated security infrastructure will play a vital role for seamless service interaction in the next generation wireless network. There are several important requirements of a successful identity management system. Such a system should be user centric rather than service centric. The user expects an integrated identity management mechanism that can handle identities for both remote and proximity service access. Security of the underlying infrastructure is also a crucial issue in wireless service access. This section has discussed all these aspects in brief.

FUTURE TRENDS

3G networks are covering a wide service area and providing ubiquitous connectivity to mobile users with low-speed data rates which is sufficient for most real-time communications. WLAN/Wi-Fi networks cover smaller areas and provide high data rates to static users. There exists a strong need for integrating WLANs/Wi-Fis with 3G networks to develop a hybrid of data networks capable of ubiquitous data services and very high data rates at strategic locations called "hotspots." The future wireless network is expected to attain this goal and thereby, seamless service access. Next generation wireless network architectures envisaged to constitute of an IP-based core network, whereas the access network can be based on a variety of heterogeneous wireless technologies depending on the nature of the access cell. In this environment, people can access many new innovative services from anywhere and anytime. Service intake will be increased significantly. Instead of current identity provisions, a new identity management mechanism is expected, especially in wireless service access.

People no longer use many usernames and passwords for remote service access. Instead SSO will become popular with the provisions of additional authentication levels to meet higher security requirements. In future identity management, the role of an identity provider will be very critical. The key issue will be who can be the identity provider? Whoever will be the identity provider, the user SIM/USIM card is in a good position to become a secure storage place for user identity information. Researchers are working to develop high capacity sophisticated smart cards to meet such demand in various service access scenarios. In this regard, it is very important to decide who will be the owner of such a user identity device (e.g., SIM/USIM). For acceptability of a SIM card as a secure identity storage place and to develop a user-centric identity management mechanism, the user should have rights to update or modify the SIM card. It is expected that the business model of the next generation network will have such flexibility. Mobile networks or other wireless access networks will play a vital role to ensure security for identity information exchange. Therefore, numerous efforts are going on to enhance the security infrastructure of access network's air interface and provide strong end-to-end protection for secure service access.

Introduction of NFC adds intelligence and networking capabilities to the phone and creates many new opportunities to add product and service capabilities to handset-like digital transactions in very good proximities. It can make the mobile phone an ideal device for payments and gaining access. Financial institutes like credit card companies and mobile manufacturers are running various trials with NFC-enabled mobile phoned in service access scenarios like admittance and payment. User identities for admittance and payment services are very sensitive in nature. Therefore, an integrated identity mechanism is expected to deal with these proximity services and as well as remote services.

Currently, the user expects and technology demands service personalization, including adaptation to personal preferences, terminal, and network capabilities. Rule-based personalization algorithms become too complex when handling user context and preferences, thus asking for new mechanisms allowing dynamic adaptability of services. Semantic descriptions of user preferences and user relations with the combination of current developments in security and privacy issues

can create more dynamic service provisions and personalization. Semantic Web is seen as the next generation of the Internet where information has machine-readable and machine-understandable semantics.

CONCLUSION

Current reporting from the World Factbook states 1.5 to two times as many mobile users as Internet users for developed countries like UK, France, and Germany and roughly three times as many mobile users as Internet users in China (The World Factbook, 2006). Taking into account that mobile users are available 24/7 as compared to an average PC usage of 137.3 min/day for male (134.2 min/day for female) shows the importance of mobile service access. The emerging next generation network is expecting to integrate various access networks including 3G and WLAN/Wi-Fi networks. Ubiquitous access for seamless service interaction will be a reality soon.

The current identity provisions will not allow this to happen. Users possess many identities in various forms and identity information is stored in a scattered way in networks. Most of the recent developments are focused towards identity management in Internet domain to access remote services. However, some efforts also target service access located in the proximity of users. The success of future service access asks for an integrated identity mechanism to deal with both remote and proximity service access. The creation of a user's role-based identity in a dynamic way and use of Semantic Web technology will enhance user experience in service interaction. Such a dynamic and integrated identity mechanism together with mobile, sensor networks, and NFC-enabled mobile terminal can improve the healthcare system for better handling of patients, especially elderly and disabled people. Semantic descriptions of user preferences and relations can also improve user experience in social interactions.

The user personal wireless device along with a sophisticated smart card will play a key role for identity management for wireless service access in terms of user identity information storage and providing secure network and service authentication. With strong encryption, privacy, and data integrity mechanisms, mobile networks have the capability to provide the underlying security infrastructure for sensitive identity information exchange for mobile users. Mobile phones equipped with custom-made high capacity SIM cards can act as a secure user identity storage place. New developments in security mechanisms to protect mishandling of user identities over the air interphase as well as over the IP-based core network can make the identity management for wireless service access secure enough.

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KEY TERMS

Authentication: Authentication is to prove as genuine.

Biometrics: Biometrics is the biological identification of a person which may include characteristics of structure and of action such as iris and retinal patterns; hand geometry; fingerprints; voice response to challenges; the dynamics of hand-written signatures, and so forth.

Circle of Trust: Circle of trust is a trust relationship through agreement among various service providers.

EAP-TLS and EAP-AKA: EAP-TLS and EAP-AKA are authentication frameworks frequently used in wireless networks.

Federation: Federation is the joining together to form a union through agreement.

IDP: Identity providers.

Life Cycle: Life cycle is the progression through a series of different stages of development.

PIN: Personal identification number.

Personalization: Personalization is when something is customized or tailored for the user, taking into consideration that person's habits and preferences.

Pervasive Computing: Pervasive computing is the use of computing devices everywhere and these devices communicate with each other over wireless networks without any interactions required by the user.

Proximity Service: Proximity services are those available close to the users.

Revocation of Identity: Revocation of identity is the act of recalling or annulling the identity.

SP: Service providers.

Single Sign-On (SSO): SSO on is the ability for users to log on once to a network and be able to access all authorized resources within the domain.

Smart Card: Smart card is a card containing a computer chip that enables the holder to perform various operations requiring data stored on chip.

Ubiquitous: Ubiquitous is being or seeming to be everywhere at the same time.

Chapter IX
Privacy-Enhancing Technique: A Survey and Classification

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ABSTRACT

This chapter provides a survey of privacy-enhancing techniques and discusses their effect using a scenario in which a charged location-based service is used. We introduce four protection levels and discuss an assessment of privacy-enhancing techniques according to these protection levels.

INTRODUCTION

Privacy is a very complex topic that touches legal, social, and technical issues. In this chapter we are focussing on the technical aspect of how to preserve privacy on the Internet. Throughout this chapter we define privacy as users' capability to determine who may know, store, and compute their data.

Privacy is one of the major concerns of Internet users (Cranor, 2000). The combination of wireless technology and Internet provides a means to combine real-world and cyber-world behaviour. Thus, extending Internet use to mobile devices is going to aggravate privacy concerns. But, privacy concerns influence also the revenue of companies which are offering their service via the Internet (Federal Trade Commission [FTC], 1999). So there is an interest in proper preserving of privacy on both sides. Especially big enterprises may suffer a lot from loss of trust in case they cannot protect the privacy-relevant data or do not adhere to their own privacy policies (Anton, He, & Baumer, 2004; Barbaro & Zeller, 2006).

Privacy-enhancing technologies (PETs) have become a hot research topic in the last few years, leading to a plethora of approaches that intend to protect privacy. This chapter provides an overview of PETs and discusses their effect on information

disclosed while using a location-based service from a mobile device. In addition, an assessment of the protection level that can be achieved by applying the introduced means is provided. Thus, this chapter helps scientists to understand what is going on in the privacy research area so they can identify new research topics more easily. In addition, it enables practitioners to find approaches that allow them to build a privacy-preserving system.

The rest of this chapter is structured as follows. We first discuss privacy protection goals and provide an example that outlines which information can be gathered while using a charged service. In the third section we explain privacy-enhancing technologies. A discussion of the protection level achieved by individual means is given in the fourth section. The chapter concludes with an investigation of the currently reached deployment of privacy-enhancing techniques and a discussion of new research challenges.

PRIVACY PROTECTION GOALS

While browsing the Web or doing e- or m-commerce every user exposes information about his/her interests, personal data, and so forth to one or several of the following service providers: network service provider, for example, telco company; Internet service provider, for example, online book store; context service provider, for example, location handling system; and payment service provider, for example, his/her bank. Perfect privacy can be achieved if and only if the user reveals no information at all. Since this excludes the user from all benefits online services provide it is not a reasonable choice. The most valuable alternative is to disclose as little information as possible and only to the service provider who essentially needs this information.

In order to achieve a reasonable good separation of information, personal data and communication habits have to be protected at network as well as at application level. The former is an essential prerequisite of the latter, that is, protection at the application level does not make any sense as long as no protection at the network level is used. Protection at application level is much more difficult to achieve than protection at the network level. Here some information has to be revealed in order to get a useful service, that is, data has to be given away and therefore it has to be protected somehow. At the application level two dimensions have to be considered to prevent detailed profiling: time and location (in the sense of data gathering entity). The time dimension hinders service providers to construct a relationship between different service uses executed by the same individual but at different points in time. The location dimension provides separation of information between several service providers so that each one of them knows only data of a specific type.

In the following subsection we discuss a service scenario in which the current position of the user is requested by the service provider, who is also charging for the service. We use this scenario to show which data is known by which party of the whole system. We will also refer to this scenario later on to illustrate the effect of the privacy-enhancing techniques discussed in the following section.

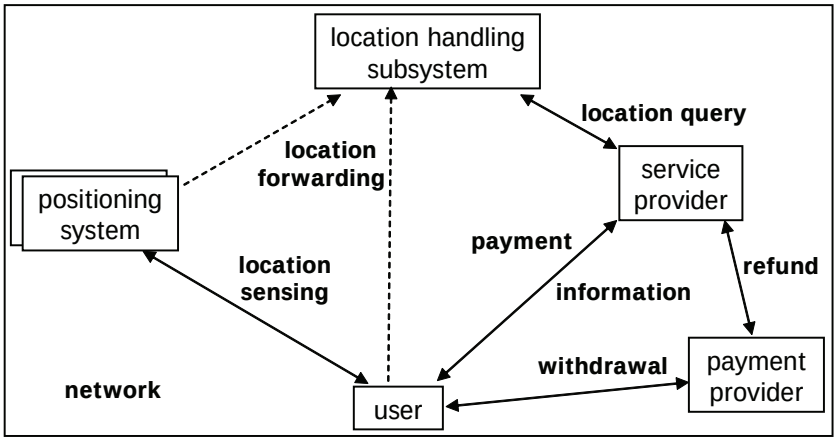
Example

In this section we present a charged location-based service scenario that shows privacy issues in detail. It shows the information flow between the involved parties and the resulting dependencies that may cause privacy flaws.

The service provides its mobile user with information that is dependent on the location of the user. Additionally, the user pays for the information using a payment protocol. As shown in Figure 1 there are five parties, besides the user, involved in this scenario.

1. Positioning system is used to sense the current location of the user. Depending on the kind of the system the location information is sent to the location handling subsystem either direct from the positioning system or is forwarded by the user. In the first case the role of the user in location information forwarding is passive, in the latter active.

Figure 1. The data exchange in the charged location-based service scenario



2. The location handling subsystem combines the location information together with the user identity. This subsystem may be a part of the service, or it may be a part of the positioning system with passive user role. Of course, it may also be a stand-alone infrastructure part that manages the location information for multiple users and provides it to multiple services.
3. The payment provider transfers money in order to allow the user to pay the service for the information.
4. The service provides the user with information based on the current location of the user received from the location handling subsystem.
5. An additional, but virtual party is the network. It may be a local network or the Internet. It may introduce parties that, generally, can be considered as eavesdroppers.

Each party of the scenario has some of the user data. In other words they have a kind of knowledge. Table 1 shows the distribution of knowledge between these parties. Additionally, if not protected by means of cryptography the user data is available to eavesdroppers.

The habits of the user are reflected in his/her location and purchase history. Even if the content of the purchased information is not known, the fact that the user communicated with or paid a specific service provider causes privacy flaws. Table 1 shows that in this scenario a detailed profiling of the user is possible if he/she always provides the same identifier to the individual service providers. So, almost every party in the scenario can create a kind of profile. The situation becomes even worse if the service providers are collaborating to get a more detailed profile of the user.

DISCUSSION OF PRIVACY-ENHANCING TECHNIQUES

In this section we provide an overview on privacy enhancing techniques but do not discuss basic technologies such as cipher means. Throughout this section we assume that all messages are encrypted in order to avoid eavesdropping and easy observation of user activities by third parties. We start with the discussion of network level protection means, before we describe application level approaches.

Network Level Privacy Protection

An often used approach intended to increase the security is the application of a proxy chain, which provides better security than use of a single proxy.

Table 1. Distribution of the knowledge about the user in the scenario. Information in brackets can also be available to the corresponding parties depending on the setup.

Party	Knowledge about the user
User	- Identity - Purchased information - Location
Positioning system	- (Location) - (Identity)
Location handling subsystem	- Location - Identity - Kind of purchased information
Service	- Identity - Purchased information - Location
Payment provider	- Identity - Kind of purchased information
network	- (Kind of purchased information) - (Identity) - (Purchased information) - (Location)

By this means the messages are forwarded from one proxy to another and eventually to the destination. Without additional security mechanisms this approach cannot be recommended since every proxy has access to data and at least the destination address, so that no protection improvement is achieved. An improvement of the proxy chain idea is the crowds approach (Reiter & Rubin, 1998). Each user runs a program called Jondo. This program is the local access of the user to the proxy network and also a proxy for other users in the network. If a Jondo proxy receives a packet it randomly decides whether to forward the packet to another Jondo or to send it to its destination. The receiver and also an external eavesdropper cannot decide whether the packet was originally sent by the direct peer or by another computer in the crowd, because the encrypted packets will be re-encrypted on every proxy. However, since every proxy still has access to content and destination address, the crowds approach still has security and privacy flaws.

In 1981 Chaum proposed mix networks as solution that solves the open issues. Mix networks are a combination of proxy chains and asymmetric cryptography. Instead of forwarding the plain message, every packet is encrypted using pubic-key cryptography (PKC). PKC allows every sender to encrypt the message with the publicly known public key of the proxy. Only the specific proxy is able to decrypt the message with the corresponding private key. The idea of mix networks is to encrypt the actual message with the public keys of a set of proxy servers (also called stages or mixes). Encryption is performed cascaded in reverse order of the mixes that will receive the packet. Additionally to the message, each encryption layer contains the address of the next mix in the chain or the final receiver. That is, first the sender encrypts the message together with the address of the receiver using the public key of the last mix in the chain, while this cipher text is encrypted together with the address of the last mix using the key of the second last mix, and

so on. Every mix only knows the previous and the next computer in the chain. No mix but the first knows the sender, and no mix but the last has information about the receiver. A single proxy is not able to disclose sender or receiver. Only with the private keys of every mix in the network it is possible to reconstruct the path from the sender to the receiver. Such alliance is unlikely if individuals or organizations with different interests administrate the mixes on the route. As long as one mix on the route does not cooperate in order to reconstruct the route the anonymity is preserved. Indeed, it is required that many users use the mix network. In order to strengthen the privacy every mix can delay and reorder messages. Due to the successive decryption on every mix recognition of forwarded packets is prevented.

Though mix networks have been matured, are available, and very safe, they also have some problems. First, the effective transfer speed is limited. While for mail applications it is not a problem and for the Web mostly acceptable, for example, real-time video streams are hardly possible. A survey on mix networks available in Sampigethaya & Poovendran (2006) provides insight into both the design and weaknesses of existing solutions.

Similar approaches such as onion routing (Reed, Syverson, & Goldschlag, 1998), crowds (Reiter & Rubin, 1998), and Web mixes (Berthold & Köhntopp, 2000) have been reported in the past. The first two are in contrast to the original mix approach vulnerable to traffic analysis attacks, but they are more efficient. The Web mixes provide the same level of privacy as mix networks, but are optimized for real-time traffic such as browsing the Web. The comparison of these approaches discussed in Berthold and Köhntopp clearly shows that better protection of user privacy comes at the cost of less efficiency.

Several projects have realized implementations of mix networks. The Tor-network ("Tor: Overview," n.d.) is a freely available open peer-to-peer (P2P) solution of a mix network. Every Internet user may open a mix server that can be part of randomly selected routes through the network. Before transmitting a packet the sender selects a route and encrypts the message with the public keys of the corresponding mixes. Both input and output mix change from connection to connection. In contrast the Java Anon Proxy (JAP) (Project: AN.ON, n.d.) uses fixed routes, termed mix cascades. The mixes are administrated by independent, well-reputed partners. Though JAP is more reliable and more trustworthy than a P2P network, it shows a weakness with respect to privacy for the user. If the last mix detects illegal content, all mixes in the cascade work together and log the incident together with the subjects.

Mix networks are probably the best way to protect privacy on the network level. On this level they are a means that provide provable perfect security. However, the gain of privacy can turn useless if privacy is not additionally protected on the application layer.

Application Layer Privacy Protection

Location Protection

In Gruteser and Grunwald (2003) an approach is presented that reduces the accuracy of location information in order to prevent re-identification of objects using location-based services. Two dimensions, that is, space and time can be modified by the system. So, instead of a single position a region is reported to the location-based service, or instead of a single point in time an interval in which the user was at a certain position is reported. The fuzzification of the data is done at a trusted server which also extracts the user identity and network address. The communication between the user and the trusted server is protected by cryptographic means and use of mix networks. The major drawback of this approach is that the trusted server knows almost everything about the user, that is, his/her identity, network address, when he/she was where, as well as which services he/she used.

Another approach, which was not actually designed for privacy on the first hand, releases position information only in case they may be actually needed (Treu & Küpper, 2005). For proximity detection of two objects that actively report their location, location updates are not necessary as

long as either of them remains in a certain circular surrounding. Consider two moving objects A and B that report their location to the infrastructure. There is a registration for a proximity event between A and B of equal or less than 1 km. Their current positions are at 101 km distance. Both objects are notified about a logical circular region with 50 km radius around their current position. These circles do not intersect and have a minimum distance of 1 km. That is, while either objects moves only within the given circle there is no chance that the objects are closer than 1 km. Hence neither of them needs to report its actual location to the infrastructure, so the location server only knows that a certain region within the user is moving and thus no detailed location tracking is possible. Since the system was not designed originally for privacy protection purposes, no means to withhold the user's identity from the server or protection of the communication between the location server and the user are investigated.

Use of Pseudonyms

The idea of pseudonyms is to hide the real identity of a user by using a bogus identity. Nicknames used in chat rooms are widely known pseudonyms. Pseudonyms prevent service providers from linking an isolated transaction to a certain user. There are several approaches that propose the use of pseudonyms in order to protect user privacy (Berthold & Köhntopp, 2000; Jendricke & Gerd tom Markotten, 2000; Jia, Brebner, & D'Uriage, 2004; Koch & Wörndl, 2001). The fundamental difference between those approaches is that Jendricke and Gerd tom Markotten and Berthold manage the different user pseudonyms at the user's own device, whereas Koch and Wörndl and Jia et al. propose the use of a centralized pseudonym service. The major drawback of systems relying on a centralized pseudonym management is that they still know the user's real identity, which services the user required and so forth, that is, they have a detailed user profile. Thus, such solutions provide only limited privacy to their users. The positive aspect of these systems is that information such as network addresses cannot be used by third parties to link pseudonyms, if the system acts as a proxy for its users as described in Jia et al.. In case of systems that still require direct interaction between their users and potential service provides such as Koch and Wörndl this benefit is no longer there. On the other hand, centralized systems provide means to identify individual users if necessary, that is, after incorrect behaviour was detected. This may help to increased acceptance of such systems on the service provider site. Decentralized approaches such as the one by Jendricke and Gerd tom Markotten allow each user to define pseudonyms himself/herself, so that there is no other entity, which has complete knowledge of real identity, and cyber world behaviour. The open issue that network addresses can be used to link pseudonyms together can be solved by additionally using mix networks.

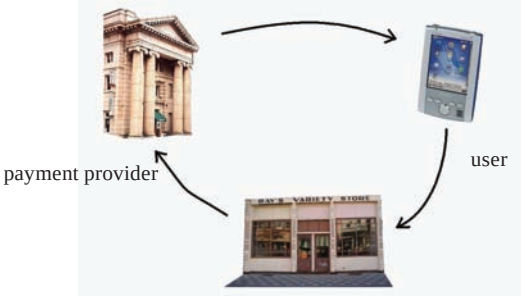
Pseudonyms are also used to realize anonymous e-cash systems, which are explained in the next paragraph.

Anonymous Payment Systems

In an electronic payment scheme there are at least three parties. Let us describe the minimum setup. The shop or service provider delivers goods or services to the user in return of a monetary equivalent by means of payment provider. Figure 2 shows the flow of the virtual money in this setup. The payment provider issues some kind of electronic money the user uses to pay the service provider for its services. There can be multiple instances of aforementioned parties, but to simplify the description only the presented flow of virtual money is assumed.

But besides the flow of the money there is also flow of information about the user. If the payment provider can recognize the electronic money tokens it issued for the user it can create a history of the service providers the user prefers. On the other hand, if the service provider can recognize the user each time the user uses the service then the history of user purchases can be created. By combining the knowledge of these two parties a complete profile of the user can be created. To avoid the possibility of profiling the user, that is, to improve

Figure 2. The flow of the virtual money in an electronic payment scheme



his/her privacy, there is a need for mechanisms that remove the link between the payments and the user identity. Thus, payment providers that use credit card like approaches, where the link to the user identity is strong, are to be avoided in privacy protecting systems.

The protection against profiling done on the payment provider side is especially important because usually during the token creation process the payment provider has access to the identity of the user. The remedy is to create the electronic money tokens in such a way that the payment provider cannot recognize them as they are returned by the service provider. The basic mechanisms that can be used for that purpose are blind signatures and anonymity as they were introduced in Chaum (1985). However, complete anonymity causes several problems, for example, the user can try to use one token twice without any consequences in case of success. To avoid this problem, improvements to the basic scheme were introduced. Revocable anonymity introduced in Brands (1993) allows linking the user identity with the token if the user used a single token twice. Generally, there is a trade-off between the security of the electronic payment scheme and the privacy level it provides to the user. As already stated, completely anonymous schemes usually suffer from security flaws. On the other hand, completely secure ones provide less privacy. Anyway, for security reasons there is a need for the inclusion of the identity of users in their tokens. This is usually done in an encrypted form that allows to reveal the user identity only in case of user misbehaviour.

To avoid the user profiling by the service provider, there is a need to remove any link between any two transactions or sets of transactions, depending on the desired granularity. To allow this, the electronic payment scheme tokens shall not contain any clue that might lead to linking any two tokens or sets of tokens that belong to the same user. Additionally, if any identification is needed, the user shall use pseudonyms while talking to the service provider. Changing the pseudonym frequent enough helps to remove the links between transactions.

Descriptive Approaches

There exist a number of technologies that do not actually protect privacy in a technical manner but rather in a descriptive way. That is, the parties involved in a data exchange agree on certain statements about the content and use of the data to be gathered, stored and /or processed. Most prominent representatives for such descriptive approaches are P3P (Cranor, Langheinrich, Marchiori, Presler-Marshall, & Reagle, 2002) and GEOPRIV (Peterson, 2005).

1. P3P/APPEL

The goal of P3P is to increase user trust and confidence in the Web. P3P provides a technical mechanism to inform users about the intended privacy policies of service providers and Web sites. The P3P specification defines the following:

- A standard schema for data a Web site may wish to collect, known as the "P3P base data schema."
- A standard set of uses, recipients, data categories, and other privacy disclosures.
- An XML format for expressing a privacy policy.
- A means of associating privacy policies with Web pages or sites, and cookies.

The P3P policy further states consequences in case of privacy breach. P3P complements legis-

lature and self-regulatory programs in helping to enforce Web site policies.

APPEL (World Wide Web Consortium [W3C], 2002) can be used to express what a user expects to find in a privacy policy. P3P and APPEL merely provide a mechanism to describe the intentions of both sides than means to protect user data after agreeing to use the service.

There are several privacy-related tools that are based on P3P and APPEL specifications. AT&T's (n.d.) Privacy Bird is a free plug-in for Microsoft® Internet Explorer. It allows users to specify privacy preferences regarding how a Web site stores and collects data about them. If the user visits a Web site, the Privacy Bird analyzes the policy provided and indicates whether or not the policy fits to the users preferences. The Microsoft® Internet Explorer 6 (Microsoft, n.d.) and Netscape® 7 (Netscape, n.d.) embed a similar behaviour. They allow the user to set some options regarding cookies and are capable of displaying the privacy policy in human readable format. All these tools are a valuable step into the right direction, but they still lack means to personalize privacy policies. Steps towards personalized privacy policies are discussed by Maaser and Langendoerfer (2005) and Preibusch (2005). In Preibusch a fine-grained choice from a set of offered policies is proposed whereas a form of a bargaining in which neither party fully publishes all its options is proposed in Maaser and Langendoefer.

Privacy policies allow for "opting-out" of or "opting-in" to certain data or data uses. But they do not provide a technical protection means. The user has no control on the actual abidance of the policy but still has to trust that his/her personal data is processed in accordance to the stated P3P policy only. Enforcement of the policy abidance could be done by hippocratic databases or other means.

2. IETFs GeoPriv

GEOPRIV is a framework (Cuellar, Morris, Mulligan, Peterson, & Polk, 2004) that defines four primary network entities: (1) a location generator, (2) a location server, (3) a location recipient, and a (4) rule holder. For appropriate interaction between those three interfaces are defined, including a publication interface and a notification interface.

GEOPRIV specifies that a "using protocol" is employed to transport location objects from one place to another. Location recipients may request a location server to retrieve GEOPRIV location information concerning a particular target. The location generator publishes location information to a location server. Such information can then be distributed to location recipients in coordination with policies set by the rule maker, for example, the user whose position is stored.

A using protocol must provide some mechanism allowing location recipients to subscribe persistently in order to receive regular notification of the geographical location of the target as its location changes over time. Location generators must be enabled to publish location information to a location server that applies further policies for distribution.

One of the benefits of this architecture is that the privacy rules are stored as part of the location object (Cuellar et al., 2004). Thus, nobody can claim that he/she did not know that access to the location information was restricted. But misuse is still possible and it is still not hindered by technical means.

Server Side Means

In order to ensure privacy after agreeing to a certain privacy policy or privacy contract suitable means on the data gathering side are needed. Such could be hippocratic databases (Agrawal, Kiernan, Srikant, & Xu, 2002), HP Select Access (Casassa, Thyne, Chan, & Bramhall, 2005), Carnival (Arnesen, Danielsson, & Nordlund, 2004), PrivGuard (Lategan & Olivier, 2002). All these systems check whether an agreed individual privacy policy allows access to certain data for the stated purpose and by the requiring entity.

There are several approaches that try to protect privacy in location-aware middleware platforms (Bennicke & Langendörfer, 2003; Gruteser & Grunwald, 2003; Langendörfer & Kraemer, 2002; Synnes, Nord, & Parnes, 2003; Wagealla, Terzis,

& English, 2003). In Langendörfer and Kraemer; Bennicke and Langendörfer; and Wagealla et al. means are discussed that enable the user to declare how much information he/she is willing to reveal. In Synnes et al. the authors discuss a middleware that uses user-defined rules, which describe who may access the user's position information and under which circumstances. The approach investigated in Gruteser and Grunwald intentionally reduces the accuracy of the position information in order to protect privacy. All these approaches lack means to enforce access to user data according to the access policy defined by users. A combination of the location-aware middleware platforms with protection means sketched previously would clearly improve user privacy. A first step in this direction was reported in Langendörfer, Piotrowski, and Maaser (2006) where users are enabled to generate Kerberos tokens on their own device and where the platform checks these tokens before granting access to user data.

ASSESSMENT OF PRIVACY-ENHANCING TECHNIQUES

In this section we discuss the protection level that can be achieved by applying privacy-enhancing techniques. In order to clarify how different classes of approaches effect user privacy we resume our example from the *Privacy Protection Goals* section and show which data is protected by which means. Thereafter we identify the protection level achieved by each class of protection means.

Evaluation of Presented Techniques

For the evaluation of the privacy-enhancing techniques we resume our example. Table 2 shows that each class of privacy-enhancing techniques has its own merit and is applicable for a specific type of information. The fact that all techniques have been designed to protect specific information allows easy combination of several approaches to improve user privacy. In the case of e-cash with revocable anonymity the use of different pseudonyms is essential in order to prevent service providers from linking individual transactions by using un-altered pseudonyms. Along these lines, the use of identity management systems becomes essential in order to ensure that all pseudonyms are used correctly, when interacting with service providers. In addition, support for the generation of pseudonyms can be of help in order to guarantee a minimal level of pseudonym quality.

In Table 2 we have not included descriptive and server-side approaches. With the former data gathered depends on user preferences and the latter provides protection against misuse only after the fact, that is, it has no influence on the data accumulated in a certain service provider's database.

Protection Level

In order to asses the protection a certain PET can provide we use a classification with four protection levels:

- **High:** Technical means are given to ensure that the amount of data that can be gathered by a service provider is restricted to a minimum or matches the user's requirements. So, no detailed information can be deduced from gathered data. The downside is that no value-added services can be provided or a service may not be provided at all.
- **Medium:** The data that are gathered can not only be determined by the user, but he/she keeps somewhat control over them. This control might be either an active data control, that is, an obeyed request for deletion, or passive control that specifies certain rules on how these data shall be dealt with in the future or for certain purposes.
- **Low:** The user can determine which of his/her data is gathered. Especially if there is no proven technical means to protect the data, it is the task of the service provider to ensure the security of the gathered data. The drawbacks for service providers could be that users are hesitant to use their service if they cannot prove the security/privacy of the data.

Table 2. The sets of user data each party can link per transaction. The positing system can get information only if the user role is passive, that is, the system tracks the user.

Party	unprotected	pseudonyms	anonymous e-cash
User	1. Identity 2. Location 3. Service provider 4. Purchase details	1. Identity 1.1 Location system user pseudonym 1.2 Service user pseudonym 1.3 E-cash user pseudonym 2. Location 3. Service provider 4. Purchase details	1. Identity 1.1 Location system user pseudonym 1.2 Service user pseudonym 2. Location 3. Service provider 4. Purchase details
Positioning system	(1); (2)	(1.1); (2)	(1.1), (2)
Location handling subsystem	1; 2; 3	1.1; 2; 3	1.1; 2; 3
Service provider	1; 2; 3; 4	1.1; 1.2; 1.3; 2; 3; 4	1.1; 1.2; 2; 3; 4
Payment provider	1; 3	3	3
Network unencrypted	1; 2; 3; 4	1.1; 1.2; 1.3; 2; 3; 4	1.1; 1.2; 2; 3; 4
Network encrypted	3	3	3
Network with MIX	-	-	-

- **None:** The user, respectively, the owner of the data, has no influence on the kind of data that is gathered, which information gets inferred or derived. In addition, the service provider or data collector respectively applies no appropriate means to protect the information or privacy. In this case we cannot speak of privacy at all. Such an environment enables service providers or others to gather as much and almost any data they want. Besides the drawback for service users having no privacy at all is it most likely diminishes the trust of the users or potential customers respectively into such services.

In the classification of the PET according to protection levels we are focussing on the strength of the classes of mechanism and neglect the side effects. We are aware of the fact that real system properties such as the number of participants have significant impact on the protection level. For example, anonymous e-cash schemes provide a high level of protection since they prevent the user's bank from learning about the users online purchase habits as well as the service provider from revealing the users identity. But if the anonymous e-cash scheme is used by a single customer of the bank only, the protection provided by the anonymous e-cash scheme collapses to the protection against the service provider, since the bank can easily link the e-coins to the user's identity.

Table 3 shows the protection level of all presented classes of privacy-enhancing techniques such as mix networks and so forth. Here we did not consider individual differences in a class since weighting individual the drawbacks of similar approaches depends much on personal preferences and technical differences are already discussed in the *Discussion of Privacy-Enhancing Techniques* section.

Table 3. Protection level of the individual privacy-enhancing techniques at network and application level

	Mix networks	Pseudonyms	Anonymous e-cash	Descriptive approaches (DA)	DA + server side technologies	Location protection
Application level	none	medium	High	low	medium	low - medium
Network level	high	none	None	none	none	none

CONCLUSION

In this chapter we have presented privacy-enhancing techniques that have evolved during the last decades. If all these techniques are combined and used in the correct way, user privacy is reasonably protected. The sad point here is that despite the fact that some of these approaches are quite well understood, they are still not in place. So despite that privacy protection is theoretically possible in the real world it is hard to achieve. Only different versions of Chaum's (1981) mix network approach and P3P (Cranor et al., 2002)/APPEL (W3C, 2002) are currently in place to protect user privacy, and experienced Internet users are using different pseudonyms while browsing the Web or doing e- or m-commerce.

From our perspective, most of the privacy-enhancing techniques still suffer from acceptance issues. Anonymous e-cash lacks support from banks. Service providers might also be reluctant to accept fully anonymous e-cash due to the challenging fraud protection mechanisms involved. Even using mix networks is problematic nowadays. Many service providers block their access if they recognize usage of mix networks. Officially it is mostly justified with crime prevention, though it can be assumed that they do not want to lose valuable additional user information.

The paradigm shift in Internet use from wired to wireless also leads to new challenges. Resource consuming, privacy-enhancing techniques cannot be applied by mobile service users. This holds especially true for use of mix networks.

New technologies such as Web 2.0 allow completely new kinds of attacks. In Rao and Rohatgi (2000) and Novak, Raghavan, and Tomkins (2004) the individual way of writing was described as a means to link pseudonyms together. As long as service users are only entering a pseudonym and an e-mail address into Web forms they are still safe, but writing exhaustive comments in news groups or blogs provides sufficient material to link pseudonyms.

Pervasive computing is going to become a real challenge for privacy-enhancing techniques. A lot of information can be gathered by the environment and up to now it is still an open issue how such an environment can be adjusted to individual privacy preferences.

ADDITIONAL READING

Additional reading can be found on the Web pages of the EU-projects, Future of Identity in the Information Society (FIDIS), Privacy and Identity Management for Europe (PRIME), and Safeguards in a World of AMbient Intelligence (SWAMI). The first two projects are focusing on identity management issues whereas SWAMI deals with privacy issues in pervasive environments. The research agenda of FIDIS (http://www.fidis.net) includes virtual identities, embodying concepts such as pseudonymity and anonymity. PRIME (https://www.prime-project.eu) aims to develop a working prototype of a privacy-enhancing identity management system. In contrast to other research projects PRIME also aims at fostering market adoption of PETs. Privacy issues in pervasive environments have not been intensively investigated by the re-

search community in recent years. A first attempt is made by the SWAMI project (http://swami.jrc.es), which focused on AMI projects, legal aspects, scenarios, and available PET.

The workshop series "Privacy Enhancing Technologies" published in Springer's LNCS series (2482, 2760, 3856, 3424, 4258) provides a great variety of publications dealing with technological, social, and legal aspects of privacy.

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KEY TERMS

Anonymous E-Cash: Electronic payment system or protocol that provides anonymity to its users.

APPEL: A language specification to define rules for acceptance of certain P3P policies.

GeoPriv: An IETF working group, which assesses the authorization, integrity and privacy requirements of transfer, release or representation of geographic location information through an agent.

Mix Networks: Ccombination of proxy chains and asymmetric cryptography that enables hard-to-trace communication over unprotected networks.

P3P: The Platform for Privacy Preferences Project (P3P) enables Websites to express their privacy practices in a standard format that can be retrieved automatically and interpreted easily by user agents.

Privacy Enhancing Techniques: Technical means that provide anonymity, intractability in networks.

Pseudonyms: Bogus identity, possible temporary, used in order to hide the real identity.

Chapter X
Vulnerability Analysis and Defenses in Wireless Networks

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ABSTRACT

This chapter shows that the security challenges posed by the 802.11 wireless networks are manifold and it is therefore important to explore the various vulnerabilities that are present with such networks. Along with other security vulnerabilities, defense against denial of service attacks is a critical component of any security system. Unlike wired networks where denial of service attacks has been extensively studied, there is a lack of research for preventing such attacks in wireless networks. In addition to various vulnerabilities, some factors leading to different types of denial of service (DoS) attacks and some defense mechanisms are discussed in this chapter. This can help to better understand the wireless network vulnerabilities and subsequently more techniques and procedures to combat these attacks may be developed by researchers.

INTRODUCTION

Due to the increasing advancement in wireless technologies, wireless communication is becoming more prevalent as it is gaining more popularity in both public and private sectors. Wireless networks are based on a technology that uses radio waves or radio frequencies (RF) to transmit or send data along a communication path. Companies and individuals are using wireless technology for important communications that they want to keep private. A recent report by a market research firm Cahners In-Stat (In-Stat, 2006) predicts sales of 802.15.4 devices (using low powered network standard) could grow by a compound annual growth rate (CAGR) of 200% from 2004 to 2009. In a similar survey, the Infornetics projected that 57% of small, 62% of medium, and 72% of large organizations in North America will be using wireless LANs (WLANs) by 2009 (Richard, 2005).

Wired networks requires a physical setup (i.e., cable wiring) for a user to get access and a misbehaved network card can be tracked down and its switch port can be disconnected remotely using network management tools. But wireless users are not connected to any physical socket, and being in an unknown location, network access can be obtained almost spontaneously. Generally speaking,

typical wireless networks are defenseless against individuals who can find unsecured networks. The wireless server dutifully grants the unauthorized computer or mobile device an IP address, and the attacker is able to launch a variety of attacks such as breaking into specific servers, eavesdropping on network packets, unleashing a worm, and denial of service (DoS) or distributed denial of service (DDoS) attacks, and so forth. In this chapter, we discuss some security threats along with DoS attacks in a typical wireless networks and survey some counter measures.

OVERVIEW OF SECURITY CHALLENGES IN WIRELESS NETWORKS

Security has traditionally consisted of ensuring confidentiality of data, the complete integrity of the data, and the availability of the data when ever needed—where service is not denied. Generally speaking, both wired and wireless network environments are complicated. Security solutions are most effective when they can be customized to a specific installation. Unfortunately, a high percentage of individuals involved in building and maintaining inter-networks and infrastructures for these environments have little knowledge of security protocols. As a result, many of today's systems are vulnerable. Recent reports indicated that the wireless networks are becoming more popular. As these networks deployments increase, so does the challenge to provide these networks with security. Wireless networks face more security challenges than their wired counterparts. This is partly due to the nature of the wireless medium as transmitted signals can travel through the walls, ceilings, and windows of buildings up to thousands of feet outside of the building walls. Moreover, since the wireless medium is airwaves, it is a shared medium that allows any one within certain distance or proximity to intrude into the network and sniff the traffic. Further, the risks of using a shared medium is increasing with the advent of available hacking tools that can be found freely from hacker's Web sites. Additionally, some default wireless access points (APs) come from the manufacturers in open access mode with all security features turned off by default. Therefore, insecure wireless devices such as APs and user stations, can seriously compromise wireless networks, making them popular targets for hackers.

Securing wireless networks requires at least three actions to be taken: first, authenticating users to ensure only legitimate users have access to the network; second, protecting the transmitted data by means of encryption; and third, preventing unauthorized connections by eliminating unauthorized transmitter or receiver. This emphasizes the need for a security framework with strong encryption and mutual authentication as explained later.

Specific Challenges and Key Issues

The security challenges in wireless networks can be roughly divided into two main categories, based on their scope and impact. The first category involves attacks targeting the entire network and its infrastructure. This may include the following:

- **Channel jamming:** This involves jamming the wireless channel in the physical layer thus denying network access to legitimate users. Typical example is the DoS attack.
- **Unauthorized access:** This involves gaining free access to the network and also using the AP to bypass the firewall and access the internal network. Once an attacker has access to the network, he/she can then launch additional attacks or just enjoy free network use. Although free network usage may not be a significant threat to many networks, however network access is a key step in address resolution protocol (ARP)-based man-in-the-middle (MITM) attacks.
- **Traffic analysis:** This attack enables gaining information about data transmission and network activity by monitoring and intercepting patterns of wireless communication. This involves analyzing the overhead wireless traffic to obtain useful information. There are three forms of information that an attacker can obtain. First, he/she can identify that there is

activity on the network. Secondly, he/she can find information about the location of APs in the surrounding area. This is because unless turned off, APs broadcast their service set identifiers (SSIDs) for identification. Thirdly, he/she may learn the type of protocols being used in the transmission.

The second category involves attacks against the communication between the stations and the AP. This may include the following:

- **Faking/replay attack:** This involves the ability to guess the structure of transmitted information (even if it is encrypted) and replace the legitimate message with one which has the correct structure but that has altered fields. This is known as faking. A simple form of faking, and one that absolutely must be protected against, is that of replay. In this, an attacker simply records and then replays a message from one legitimate party to another. A new form of replay attack is known as ***wormhole*** attack. In this attack, the attacker records packets or individual bits from a packet at one location in the network, tunnels them to another location, and replays it there as described in Yih-Chun (2006).
- **Eavesdropping:** This implies the interception of information/data being transmitted over the wireless network. When the wireless link is not encrypted, an attacker can eavesdrop the communication even from some few miles away. The attacker can gain two types of information from this attack; he/she can read the data transmitted in the session and can also gather information indirectly by examining the packets in the session, specifically their source, destination, size, number, and time of transmission. Eavesdropping can also be active; in this case the attacker not only listens to the wireless connection, but also actively injects messages into the communication medium.
- **Man-in-the-middle attack (MITM):** In this attack, the attacker resides between the station and the AP, and can intercept and modify the message, then release the modified message to the target destination. This can be done by setting a rogue AP as described in Lynn and Baird (2002).
- **Message forgery:** In this attack, as the wireless link is not protected for message integrity, an attacker can inject forged messages into both directions of the communication.
- **Session hijacking:** In this attack, an attacker causes the user to lose his/her connection, and he/she assumes his/her identity and privileges for a period. It is an attack against the integrity of a session. The target knows that it no longer has access to the session but may not be aware that the session has been taken over by an attacker. The target may attribute the session loss to a normal malfunction of the WLAN.

Analysis of Wired Equivalent Privacy (WEP) Protocol

Wired equivalent privacy (WEP) has been part of the 802.11 standard since its initial ratification in September 1999. It is designed for data privacy and encryption to protect messages form unauthorized viewing in case they are intercepted in the air. Its goals are to provide integrity, availability, and confidentiality to the wireless networks. However, notable security research findings have shown deficiencies and flaws in the design of WEP (Fluhrer, Mantin, & Shamir, 2001; Gast, 2002, pp. 93-96).

War Driving and Its variants

The process of identifying and categorizing the wireless networks by using pre-configured laptops from within a moving vehicle is called war driving. War drivers use laptops and some special software to identify wireless networks and let them understand the security associated with any particular wireless network that they have recorded. They also upload their war driving results to a Web site where others who have access will be able to see exactly where these unsecured wireless networks are located. The use of GPS has aided this objective even further.

War driving Web site http://www.worldwidewardrive.org has done the data collection during four rounds of war driving world wide from 2002 to 2004. Their first worldwide war driving started on August 31 and finished on September 7, 2002. During this time, 9,374 APs were located and in only 30.13% had WEP encryption enabled. The second drive lasted from October 26 to November 2, 2002 when they tracked 24,958 APs, with only 27.2% having WEP enabled. During the third drive which happened from June 28 to July 5, 2003, 88,122 APs were located with only 32.26% WEP enabled. The fourth drive started in June 2004 for some months, located 228,537 APs and the total number of wireless networks running WEP was found to be 38.3%.

Security Enhancements

In the context of the aforementioned deficiencies, an IEEE 802.11i or IEEE 802.11 Task Groupi (TGi) developed a new set of WLAN security protocols to form the future IEEE 802.11i standard. The new security standard, 802.11i, which was confirmed and ratified in June 2004, eliminates all the weaknesses of WEP. It is divided into three main categories (Strand, 2004) and these enhancements are described as follows:

1. **Temporary key integrity protocol (TKIP):** This is essentially a short term solution that fixes all WEP weaknesses. It would be compatible with old 802.11 devices and it provides integrity and confidentiality.
2. **Counter mode with cipher block chaining-message authentication code protocol (CCMP):** This is a new protocol designed with planning, based on RFC 2610 which uses Advanced Encryption Standard (AES) as cryptographic algorithm. Since this is more CPU intensive than RC4 (used in WEP and TKIP), new and improved 802.11 hardware may be required. It provides integrity and confidentiality.
3. **Extensible authentication protocol (EAP):** EAP is a general protocol for point-to-point (PPP) authentication that supports multiple authentication mechanisms.

Temporary Key Integrity Protocol (TKIP)

Wi-Fi protected access (WPA) was designed to replace WEP with the combination of the TKIP, which provides data confidentiality through encryption, and a new cryptographic message integrity code called MIC or Michael, which provides data integrity. TKIP comprises the same encryption engine and RC4 algorithm defined for WEP. However, unlike WEP the TKIP uses a 128 bits key for encryption and 64 bits key for authentication. This solves the problem of a shorter WEP key. TKIP also added a per-packet key mixing function to de-correlate the public initialization vectors (IVs) from weak keys. Furthermore, TKIP also provides a rekeying mechanism to provide fresh encryption and integrity keys by giving each user a unique shared key per session and by using IV as a counter. It discards any IV value received out of sequence. If the IV space is exhausted, a new key is negotiated. This makes TKIP protected networks more resistant to cryptanalytic attacks involving key reuse. TKIP provides better security than the WEP by adding four new algorithms:

- It provides a nonlinear hash function (Michael) that produces a 64 bit output. Unlike CRC used in WEP, Michael is keyed. Only those who know the secret key can compute a valid hash.
- It provides a new IV sequencing discipline to remove replay attacks from the attacker's arsenal.
- It also has a per-packet key mixing function to de-correlate the public IVs from weak keys.
- Finally, it provides a rekeying mechanism, to provide fresh encryption and integrity keys, undoing the threat of attacks stemming from key reuse.

Table 1 shows how WPA uses TKIP and Michael to address the cryptographic weaknesses of WEP (Cable, 2004).

Counter CBC-MAC Mode

Counter with cipher block chaining-message authentication code or simply (CCM) is a mode

Table 1. WPA vs. WEP

WEP weakness	How weakness is addressed by WPA
IV is too short	In TKIP, the IV has been doubled in size to 48 bits.
Weak data integrity	The WEP-encrypted CRC-32 checksum calculation has been replaced with Michael. The Michael algorithm calculates a 64-bit message integrity code (MIC) value, which is encrypted with TKIP
Uses the master key rather than derived key	TKIP and Michael use a set of temporal keys that are derived from a master key and other values. The master key is derived from the extensible authentication protocol-transport layer security (EAP-TLS) or Protected EAP (PEAP) 802.1X authentication process. Additionally, the secret portion of the input to the RC4 PRNG is changed with each frame through a packet mixing function.
No rekeying	WPA rekeys automatically to derive new sets of temporal keys.
No replay protection	TKIP uses the IV as a frame counter to provide replay protection.

of operation for a symmetric key block cipher algorithm. CCM may be used to provide assurance of the confidentiality and the authenticity of computer data by combining the techniques of the counter (CTR) mode and the cipher block chaining-message authentication code (CBC-MAC) algorithm. CCM is based on an approved symmetric key block cipher algorithm whose block size is 128 bits, such as the AES. CCM consists of two related processes: generation-encryption and decryption-verification, which combine two cryptographic primitives: counter mode encryption and cipher block chaining based authentication. Only the forward cipher function of the block cipher algorithm is used within these primitives. In generation-encryption, cipher block chaining is applied to the payload, the associated data, and a nonce to generate a message authentication code (MAC); then, counter mode encryption is applied to the MAC and the payload to transform them into a ciphertext. Thus, CCM generation-encryption expands the size of the payload by the size of the MAC. In decryption-verification, counter mode decryption is applied to the purported ciphertext to recover the MAC and the corresponding payload; then, cipher block chaining is applied to the payload, the received associated data, and the received nonce to verify the correctness of the MAC. Successful verification provides assurance that the payload and the associated data originated from a source with access to the key (Dworkin, 2004).

CCMP is the preferred encryption protocol in the 802.11i standard. CCMP is based upon the CCM mode of the AES encryption algorithm. Thus, CCMP utilizes 128-bit keys, with a 48-bit IV. As with the CCM, confidentiality and authentication are provided by the counter mode (CM) and the cipher block chaining message authentication code (CBC-MAC).

CCMP addresses all known WEP deficiencies, but without the restrictions of the already-deployed hardware. The protocol has many properties in common with TKIP (Cam-Winget et al., 2003). WEP, TKIP, and CCMP can be compared as in Table 2.

802.1x/EAP Authentication

IEEE 802.1x was created for authentication in PPP. It ties a protocol called EAP, which can be applied to both the wired and wireless networks. It also supports multiple authentication methods, such as EAP-Message Digest (EAP-MD5), EAP-One Time Password (EAP-OTP), EAP-Transport Layer Security (EAP-TLS), EAP-Tunneled TLS (EAP-TTLS), EAP-Generic Token Card (EAP-GTC), Microsoft CHAP version 2 (EAP-MSCHAPv2), and EAP-FAST (Blunk & Vollbrecht, 1998).

In 802.1x EAP authentication process, a client attempts to connect with an authenticator (AP). The AP responds by enabling a port for passing only EAP packets from the client to an authentication server located on the wired side of the AP. The AP blocks all other traffic, such as HTTP, DHCP, and POP3 packets, until the AP can verify the client's identity using an authentication server (e.g., RADIUS). Once authenticated, the AP opens the client's port for other types of traffic. The summary of the process is as shown in Figure 1.

Table 2. WEP, TKIP, and CCMP comparison (Cam-Winget, Housley, Wagner, & Walker, 2003)

	WEP	TKIP	CCMP
Cipher	RC4	RC4	AES
Key size	40 or 104 bits	128 bits encryption, 64 bits authentication	128 bits
Key lifetime	24-bit IV, wrap	48-bit IV	48-bit IV
Packet key integrity	Concatenating IV to base key	Mixing function	Not needed
Packet data	CRC-32	Michael	CCM
Packet header	None	Michael	CCM
Replay detection	None	Use IV sequencing	Use IV sequencing
Key management	None	EAP-based (802.1x)	EAP-based (802.1x)

- Client or supplicant sends an association request to the authenticator (AP)
- The authenticator or AP replies with associated response to the supplicant (client)
- Supplicant sends an EAP-start message to the authenticator
- The authenticator replies with an EAP-request identity message
- The supplicant sends an EAP-response packet containing the received identity to the authentication server
- The authentication server uses a specific authentication algorithm to verify the client's identity
- The authentication server will either send an acceptance or rejection message to the AP
- The AP sends an EAP-success packet (or reject packet) to the client

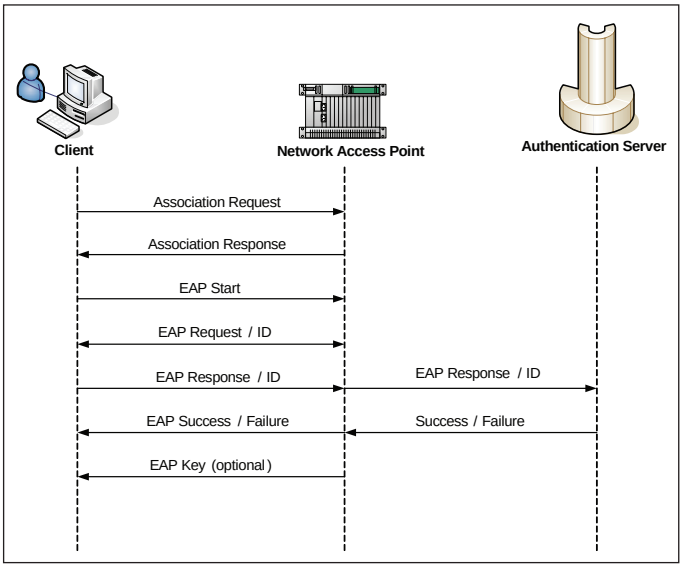
If the authentication server accepts the client, then the AP will transition the client's port to an authorized state and forward additional traffic. However, potential for MITM attacks in tunneling EAP protocols such as PEAP and EAP-TTL are documented in an IACR report that is available online (http://eprint.iacr.org/2002/163/).

Other Protocols

This section will briefly introduce other protocols that are being used or being developed in securing wireless networks.

- **TIK protocol:** TESLA with instant key disclosure protocol or simply TIK protocol was proposed in Yih-Chun (2006). It is an extension of the TESLA broadcast authentication protocol (Perrig, Canetti, Tyger, & Song, 2000). It implements temporal leashes and provides efficient instant authentication for broadcast communication in wireless networks. The intuition behind TIK is that the packet transmission time can be significantly longer than the time synchronization error. In these cases, a receiver can verify the TESLA security condition (that the corresponding key has not yet been disclosed) as it receives the packet; this fact allows the sender to disclose the key in the same packet. TIK implements a temporal leash and, thus, enables the receiver to detect a wormhole attack. It is based on efficient symmetric cryptographic primitives (a message authentication code is a symmetric cryptographic primitive). It requires

Figure 1. General EAP authentication process



accurate time synchronization between all communicating parties, and requires each communicating node to know just one public value for each sender node, thus enabling scalable key distribution.

- **SSTP protocol:** Microsoft is working on a remote access tunneling protocol that allows client devices to securely access networks via a *virtual private network* (VPN) from anywhere on the Internet without any issues with typical port blocking problems. The secure socket tunneling protocol (SSTP) makes a VPN tunnel that goes over Secure-HTTP, eliminating issues associated with VPN connections based on the point-to-point tunneling protocol (PPTP) or layer 2 tunneling protocol (L2TP) that can be blocked by some Web proxies, firewalls, and network address translation (NAT) routers that sit between clients and servers. The protocol is only for remote access and will not support site-to-site VPN tunnels. (Fontana, 2007)

Other Attacks on Wireless Security

There are some other effective attacks that can be launched against 802.11 wireless networks and they are briefly explained next (Earle, 2006).

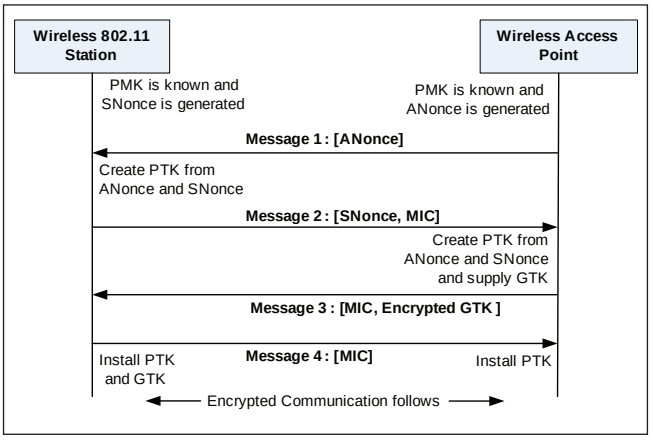
WPA Passive Dictionary Attack

This attack can be launched against a WPA pre-shared key (with four-way handshake) setup in 802.11g networks using a dictionary file of words (Takahashi, 2004). As a precaution, avoid dictionary words for the pass phrase during AP configuration and make pass phrase more than 20 characters.

The process of the four-way handshake shown in Figure 2 can be explained as follows. The AP and communicating station need an individual pairwise transient key (PTK) to shield the unicast conversation between them. To come out with a different PTK for each AP-station pair, a pairwise master key (PMK) is included in the algorithm, along with MAC address, ANonce, and SNonce (two random values). The first two messages manage to derive the same PTK without transmitting in the air. The AP also generates a group transient key (GTK) to shield all conversations, especially multicast and broadcast. As all stations on the wireless network needs that same GTK to decrypt broadcast or multicast frames, the AP sends the current GTK in the third message of the handshake.

To stop someone from hacking the communication, the GTK is encrypted with the PTK. To avoid forgery in these handshake messages,

Figure 2. WPA-PSK four-way handshake



second, third and fourth messages have a message integrity code (MIC). The MIC is generated by hashing a specified portion of the message and then encrypting that hash with the PTK. This four-way handshake occurs whenever someone connects to a WLAN using WPA. It also occurs thereafter, whenever the AP decides to refresh the transient keys (Phifer, 2007).

Attack on Michael MIC

Michael MIC was introduced to prevent attacks through message modification. It uses a feature known as TKIP countermeasure procedure, which works by disabling the AP if it receives two MIC failures within one second. After exactly one minute, the AP comes back to life and would need all its past and current users to re-key to gain access to the network. An attacker could send corrupt packets to the AP which can pass the frame CRC check, but would trigger the TKIP countermeasure eventually shutting down the AP, especially after repeated corrupt traffic.

Encryption Attacks on Known Plaintext, Double Encryption, and Message Modification

For WEP encryption process, an XOR operation of message (or plaintext) with encryption key is done. For decryption process, the encrypted text is XOR-ed with the key to get the plaintext. Firstly, the known plaintext attack is done when the attacker knows two things: cleartext and the encrypted text of a message communication. Having both the encrypted and unencrypted form of the same information allows one to perform this attack and to retrieve the encryption key. The attacker needs to XOR cleartext and encrypted text to get the key. Secondly, to carryout the double encryption attack, a frame must be captured and the attacker must change the frame header destination MAC address to that of the attacker's wireless client. After this subtle change, the attacker must wait for the IV to reset to one minus the original IV (of the modified frame), so that he/she can replay the captured frame into the air. When the AP sees the frame with the expected IV, it will encrypt the frame, actually being fooled into decrypting the frame instead of encrypting it. After doing the unknowing decryption process, the AP will forward the cleartext frame across the air to the forged MAC address specified by the attacker. Thirdly, to achieve the message modification attack, the attacker must capture an encrypted packet that is going to another subnet, modify a single bit, and attempt to resend it. The modification will offset the IC and the packet will be rejected. After trying a number of times, the bits that are flipped will make the IC correct again, although the packet would be malformed. The attacker can do this numerous

times without any logging or alerts from the AP. Once the packet passes the AP's IC check, it will reach the route. The router will observe that the packet is malformed and would send a response that contains the cleartext and associated encrypted text packet to the initial sender. This will give the attacker the ingredients to perform cleartext cryptanalysis. A solution is to encrypt the 802.11 frames within a layer 3 (network layer) wrapper, so that any tampering cannot go undetected.

General WLAN Security Measures

General security measures to minimize some of the mention flaws are listed as follows (Held, 2003; Hurton & Mugge, 2003; Issac. Jacob, & Mohammed, 2005):

1. Encrypt the network traffic. WPA with TKIP/AES options can be enabled. Upgrade the firmware on AP to prevent the use of weak IV WEP keys.
2. Ensuring mutual authentication through IEEE 802.1x protocol. Client and AP should both authenticate to each other. Implementing IEEE 802.1x port-based authentication with RADIUS server (with PEAP/MS-CHAPv2) would be a good choice.
3. Make the wireless network invisible by disabling identifier broadcasting. Turning off the SSID broadcast by AP and configure the AP not to respond to probe requests with SSID "any," by setting your own SSID. Meaning, rename the wireless network and change the default name.
4. Changing the default WEP key settings, if any. Changing the default IP address in the AP to a different one. Change administrator's password from the default password. If the wireless network does not have a default password, create one and use it to protect the network.
5. Enabling the MAC filtering in AP level or in RADIUS server or in both can tighten the security more, as there is a restriction in the use of MAC addresses (this step in itself, can be defeated through MAC spoofing).
6. Positioning and shielding of the antenna can help to direct the radio waves to a limited space.
7. Enabling of accounting and logging can help to locate and trace back some mischief that could be going on in the network. Preventive measures can then be taken after the preliminary analysis of the log file. Allow regular analysis of log files captured to trace any illegal access or network activity.
8. Using intrusion detection software to monitor the network activity in real time and to inform alerts.
9. Using honey pots or fake APs in the regular network to confuse the intruder so that he/she gets hooked to that fake AP without achieving anything.
10. Turn off the network during extended periods of non-use or inactivity.
11. Use file sharing with caution. If the user does not need to share directories and files over the network, file sharing should be disabled on his/her computers.
12. Do not auto-connect to open Wi-Fi (wireless fidelity) networks.
13. Connect using a VPN as it allows connecting securely. VPNs encrypt connections at the sending and receiving ends through secure tunnels.
14. Use firewalls in between wireless and wired network segments and implement filters.
15. Generally avoid dictionary words for pass phrase in any authentication. Also make the pass phrase more than 20 characters, especially if WPA-Pre Shared Key security is employed.

TYPES OF DENIAL OF SERVICE ATTACKS AND PREVENTIVE MEASURES

DoS simply means the inability of a user, process, or system to get the service that it needs or wants. Common DoS attacks on networks include direct attacks, remote controlled attacks, reflective attacks, and attacks with worms and viruses.

DoS attacks are quite effective against wireless networks. The wireless management frames which are transmitted in cleartext in a wireless network, informs the clients that they can connect or disconnect. The de-authentication frame will disassociate a wireless end device from an AP. Since they are sent in cleartext, they can easily be forged to force legitimate users out of the network. This can be accomplished by replaying a previous disassociation frame with a wireless sniffer. An attack on 802.11b with 802.11g mixed network mode can affect the clear channel assessment (CCA) process that brings down the probability that two wireless nodes will transmit on the same frequency simultaneously. This attack can cause all nodes in range to shut down until the attacker stops injecting the malicious frame. A layer 2 encryption would be the only solution to this. The EAP-DoS attack involves injecting a number of EAP stat frames to an AP and if the AP cannot properly process all these frames, there is the chance that it might become inoperable. Another attack against the AP involves sending malformed EAP messages. One of the recent attacks against the AP involves filling up the EAP identifier space that allows 255 ID tags to keep track of each client instance. If an attacker can flood the AP with a large number of client connection instances, using up this counter, a DoS attack can be achieved (Earle, 2006).

Different researchers have categorized DoS and DDoS from different perspectives. As documented in Christos and Aikaterini (2003), DoS attacks can be classified into five different categories, namely: (1) network device level attack, (2) operating system (OS), level attack, (3) application level attack, (4) data flood attack, and (4) protocol attack.

Network device level attack includes attacks that might be caused either by taking advantage of bugs or weaknesses in driver software or by trying to exhaust the hardware resources of network devices. Network level attacks may also involve compromising a series of computers and placing an application or agent on the computers. The computer then listens for commands from a central control computer. The compromise of computers can either be done manually or automatically through a worm or virus.

The OS level DoS attacks rely on the ways operating systems implement protocols. A typical example is the ping of death attack in which Internet control message protocol (ICMP) echo requests having total data sizes greater than the maximum IP standard size to be sent to the targeted victim. This attack often has the effect of crashing the victim's machine.

In application-based attacks, machine or a service are compromised and set out of order either by taking advantage of specific bugs in network applications that are running on the target host or by using such applications to drain the resources of their victim. It is also possible that the attacker may have found points of high algorithmic complexity and exploits them in order to consume all available resources on a remote host.

In data flooding attacks, an attacker uses all network bandwidth or any other device bandwidth by sending massive quantities of data and so causing it to process extremely large amounts of data. For instance, the attacker bombards the targeted victim with normal, but meaningless packets with spoofed source addresses.

DoS attacks based on protocol features take advantage of certain standard protocol features such as IP and MAC source addresses. Typically, the attacker spoofs these features. Several types of DoS attacks have focused on domain name systems (DNSs), and many of these involve attacking DNS cache on name servers. An attacker who owns a name server may coerce a victim name server into caching false records by querying the victim about the attackers own site. A vulnerable victim name server would then refer to the rogue server and cache the answer (Davidowicz, 1999).

Other researchers such as Papadimitratos and Hass (2002) and Marti, Giuli, Lai, and Baker (2001) describe DoS attacks in relation to routing layer and those at the link or MAC layer.

Attacks at the routing layer could consist of the following: (1) the attacker participates in routing and simply drops a certain number of the data packets. This causes the quality of the connections to deteriorate and further ramifications on the performance if TCP is the transport layer protocol that is used; (2) the attacker transmits falsified route

updates. The effects could lead to frequent route failures thereby deteriorating performance; (3) the attacker could potentially replay stale updates. This might again lead to false routes and degradation in performance; and (4) reduce the time-to-live (TTL) field in the IP header so that the packet never reaches the destination. Routing attacks are usually directed at dynamic routing protocols such as border gateway protocol (BGP), open shortest path first (OSPF), and enhanced interior gateway routing protocol (EIGRP). Direct DoS or DDoS attacks against routing protocols can lead to regional outages. Another form of routing attack is called route injection, which can lead to traffic redirection, prefix hijacking, and so forth. Attacks at the MAC layer are described next.

Flooding and Spoofing Attacks

Flooding attack, as the name implies, involves the generation of spurious messages to increase traffic on the network. While spoofing attacks involves the creation of packets with spoofed (i.e., forged) source IP addresses and other credentials.

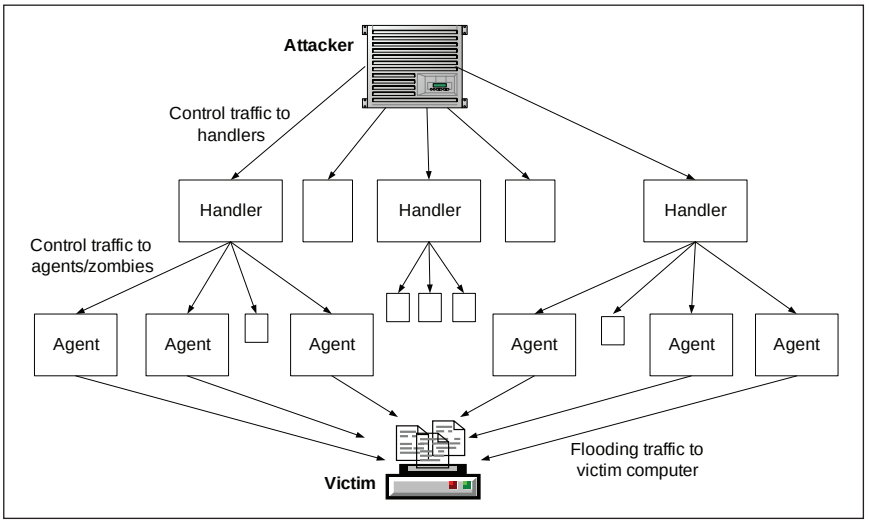
In smurf attack, an attacker sends a large amount of ICMP echo traffic to a set of IP broadcast addresses, multiplying the traffic by the number of hosts responding. ICMP flooding attack uses public sites that respond to ICMP echo request packets within an IP network to flood the victim's site. It involves flooding the buffer of the target computer with unwanted ICMP packets. SYN flood attack is also known as the transmission control protocol (TCP) SYN attack and is based on exploiting the standard TCP three-way handshake. In this case, an attacker sends SYN packet to initiate connection. The victim responds with the second packet back to the source address with SYN-ACK bit set. The attacker never responds to the reply packet. In this case, the victim's TCP receive queues would be filled up, denying new TCP connections. Another variant of this attack is called user datagram protocol (UDP) flooding attack (Craig, 2000). This attack is based on UDP echo and character generator services provided by most computers on a network. In MAC spoofing attack, an attacker spoofs his/her original MAC address to the MAC address he/she wants to spoof. An attacker can learn the MAC address of the valid user by capturing wireless packets using any packet capturing software by passively or actively observing the traffic. Web spoofing permits an attacker to observe and change all the Web traffic sent to the victim's machine and capture all data entered into the Web page forms (if any) by the victim. The attack can be done using Web plug-ins and JavaScript segments. The attack, once implemented, is started when the victim visits a malicious Web page through a Web link in a malicious e-mail message sent by the attacker. DNS spoofing is where the attacker makes a DNS entry to point to another IP address than it would be generally pointing to. It works through stealth by unknowingly forcing a victim to generate a request to the attacker's server, and then spoofing the response from that server. IP spoofing is a process used to gain unauthorized access to computers, whereby the attacker sends packets to a computer with spoofed IP address implying that the message is coming from a trusted and genuine host.

DDoS Attack

DDoS attacks usually refer to an attack by use of multiple sources that are distributed throughout the network. In this attack, an attacker installs the DDoS software controls on a network of computers, mostly through security compromise. This allows the attacker to remotely control compromised computers, thereby making it handlers and agents. From a "master" device, the attacker can control the slave devices and direct the attack on a particular victim. Thousands of machines can be controlled from a single point of contact as shown in Figure 3. There are several types of DDoS attacks, but their methods are very similar in that they rely on a large group of previously compromised systems to direct a coordinated distributed flood attack against a particular target.

Christos and Aikaterini (2003) classified DDoS based on the degree of the attack automation. These classifications are manual, semi-automatic, and automatic DDoS attacks. The manual attack involves manual scanning of remote machines for

Figure 3. DDoS attack scenario using agents/zombies to flood the victim



vulnerabilities, then the attacker breaks into anyone of them to install attack codes. Semi-automatic attacks are partially manual and partially automatic. In this case, the attacker scans and compromises handlers and agents by using automated scripts. He/she then types the victims address manually and the onset of the attack is specified by the handler machines. In automatic DDoS attacks the communication between attacker and agent machines is completely avoided. In most cases the attack phase is limited to a single command through the attack code file. All the features of the attack, for example the attack type, the duration, and the victims address are preprogrammed in the attack code. This way, the possibility of revealing the attacker's identity or source is very minimal. A number of DDoS tools that are available from the Internet have been identified by the Internet Security Systems (ISS) (www.iss.net).

Defense Mechanisms Against DoS Attacks

Several techniques to counter DoS and DDoS attacks have been proposed by researchers, and we briefly discuss some of these techniques. A challenge based mechanisms was proposed by Kandula, Katabi, Jacob, and Berger (2005). For example, an image-based challenge may be used to determine whether the client is a real human being or an automated script. A similar approach based on capabilities was proposed in Agarwal, Dawson, and Tryfonas (2003), and the method generally relies on clients having to ask the server for permission to send packets. If the server decides to allow the connection, it replies with a capability token, which the client includes in subsequent packets and which the network polices.

Greenhalgh, Handley, and Huici (2005) described an approach consisted of diverting traffic going to protected servers so that it traverses control points. These control points would encapsulate the traffic, sending it to a decapsulator near the server. The server could then tell which control point a malicious flow had traversed, and request it be shut down at this boundary. Signature-based and anomaly based detection techniques are proposed in Park and Lee (2001) and Shields (2002). Some solutions involve the use of strong digital signature based transport level authentication mechanisms as recently proposed in Dierks and Allen (2006).

Mechanisms Against Spoofing

Attackers launching spoofing usually hide the identity of machines they used to carry out an

attack by falsifying the source address of the network communication. This makes it more difficult to identify the sources of attack traffic. It is therefore important to use network switches that have MAC binding features that store the first MAC address that appears on a port and do not allow this mapping to be altered without authentication. To prevent *IP spoofing*, disable source routing on all internal routers and use ingress filtering. *Web spoofing* depends mainly upon social engineering tricks and it is thus important to educate users and to be generally aware of the address window in a browser that displays the Web address that they are directed to. That can help if some suspicious Web site address comes up. *DNS spoofing* can be prevented by securing the DNS servers and by implementing anti-IP address spoofing measures (Paul, Ben, & Steven, 2003). Some vendors have added access control lists (ACL), implemented through MAC address filtering, to increase security. MAC address filtering amounts to allowing predetermined clients with specific MAC addresses to authenticate and associate. While the addition of MAC address filtering increases security, it is not a perfect solution given that MAC addresses can be spoofed. Also, the process of manually maintaining a list of all MAC addresses can be time consuming and error prone. Therefore MAC address filtering is probably best left for only small and fairly static networks (Mohammed & Issac, 2005).

Filtering Techniques

Filtering requires being able to filter the flood packets. This can be achieved with a signature-based packet filter. If one can create signatures for typical flood packets (TCP packets with zero data size for example, or unusually large ICMP packets), and filter out those packets, one can then filter the flood packets while allowing "normal" traffic to proceed.

Another filtering option is to reject the first IP packet from any IP address. This works with many current generations of attack tools because they tend to use a flat distribution random number generator to generate spoofed source addresses, and they only use each random address once. Another possibility is to divert traffic based on IP protocol to different servers or even route it differently. Thus, for a Web server it might be possible to route ICMP and UDP traffic bound for the Web server somewhere else entirely, or even block it at the router, so that only TCP-based floods will succeed. This at least narrows the scope of attacks that can be made.

Another filtering technique is called ingress filtering. This filtering prevents spoofed attacks from entering the network by putting rules on point-of-entry routers that restrict source addresses to a known valid range.

Filtering can also be based on channel control. This method is known as channel control filtering and can be achieved by filtering out DDoS control messages; this prevents the attacker from causing the attack servers to begin the attack. This can also be accomplished using a signature-based packet filter. If we can develop signatures for most control channel packets, we can simply reject them at the control channel packet filter, and they will disappear from the network.

FUTURE TRENDS

Due to the rapid changes in treat level and attacking techniques, existing defense mechanisms may not be adequate to counter the threats of the future attacks. Therefore, it is important for researchers to continue analyzing different threats as they emerge and develop more effective and efficient defense mechanisms. For instance, detecting distributed and automated attacks still remains a challenge. Due to the drawback of some of the exiting solutions or defense mechanisms as well as the emergence of new attack tools, further study is needed to combine well-known security drawbacks with defense techniques that are already mature and very effective. Moreover, it is also important to look into the developing of DoS management framework for protecting, detecting, and reacting to attacks when they occur. The following summarizes expected future trends in DoS and DDoS attacks—attacks on emerging technologies; attacks against anti-DoS infrastructure; attacks with the

aid of malware, adware, or spyware; recursive DNS attacks or the use of DNS server for DoS attack; and attacks against OpenEdge WebSpeed platforms, and so forth.

CONCLUSION

This chapter explores some of the security vulnerabilities associated with 802.11 wireless networks. Here basic issues with WEP and better protocols like TKIP and CCMP were discussed with some advice on security precautions. Later emphasis was given on DoS and DDoS attacks to show how complicated and varied they are in nature. DoS attacks are done quite effectively against wired and wireless networks and it costs much in terms of the damages done. Defense mechanisms against such attacks are still not perfect and the chapter eventually reviews and explains some sets of defense mechanisms that could help against such attacks.

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http://www.cert.org/archive/pdf/DoS_trends.pdf

http://www.cert.org/research/isw/isw2000/papers/42.pdf

Other links

http://www.kb.cert.org/vuls/

http://www.usenix.org/publications/login/2000-7/apropos.html

http://www.iss.net

http://www-1.ibm.com/services/continuity/recover1.nsf/files/Downloads/$file/DOS.pdf

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KEY TERMS

Denial of Service (DoS): Denial of service are attacks to prevent legitimate users from receiving services from the service provider.

Distributed Denial of Service (DDOS): DDOS is a type of DoS attack conducted by using multiple sources that are distributed throughout the network.

Flooding Attack: Flooding attack involves the generation of spurious messages to increase traffic on the network for consuming server's or network's resources.

Information Security: Information security is a mechanism dealing with providing confidentiality, integrity, authentication, and non-repudiation.

Network Security: Network security is a mechanism dealing with protection of the networking system as a whole and sustaining its capability to provide connectivity between the communicating entities.

Spoofing Attack: Spoofing attack involves the creation of packets with a forged or faked source IP addresses.

Wireless Networks: Wireless networks are based on a technology that uses radio waves or radio frequencies to transmit or send data.

Chapter XI
Key Distribution and Management for Mobile Applications

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ABSTRACT

This chapter deals with challenges raised by securing transport, service access, user privacy, and accounting in wireless environments. Key generation, delivery, and revocation possibilities are discussed and recent solutions are shown. Special focus is on efficiency and adaptation to the mobile environment. Device domains in personal area networks and home networks are introduced to provide personal digital rights management (DRM) solutions. The value of smart cards and other security tokens are shown and a secure and convenient transmission method is recommended based on the mobile phone and near-field communication technology.

A PROBLEM OF MEDIA ACCESS

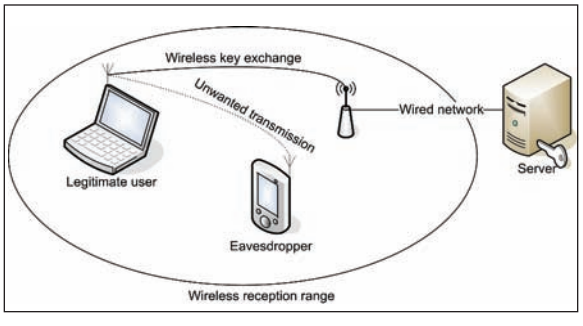
On the dawn of ubiquitous network access, data protection is becoming more and more important. While in the past network connectivity was mainly provided by wired connections, which is still considered the most secure access method, current and future users are moving towards wireless access and only the backbone stays connected by wires. In a wired environment, eavesdropping is existent, but not as spread and also not easy to implement. While methods exist to receive electromagnetic radiation from unshielded twisted pair (UTP) cables, a quite good protection can be achieved already by transport layer encryption or deploying shielded twisted pair (STP) or even fibre.

New technologies emerged in the wireless world, and especially the IEEE 802.11 family has drastically changed the way users connect to networks. The most basic requirements for new devices are the capability of supporting wireless service access. The mobile world introduced general packet radio service (GPRS) and third generation (3G) mobile systems provide permanent IP connectivity and provide together with Wi-Fi access points continuous wireless connectivity. Besides communications devices such as laptops, phones, also cars, machines, and home appliances nowadays come with wireless/mobile connectivity.

Protecting user data is of key importance for all communications, and especially for wireless communications, where eavesdropping, man-in-the-middle, and other attacks are much easier. With a simple wireless LAN (WLAN) card and corresponding software it is possible to catch, analyse, and potentially decrypt wireless traffic. The implementation of the first WLAN encryption standard wired equivalent privacy (WEP) had serious weaknesses. Encryption keys can be obtained through a laptop in promiscuous mode in less than a minute, and this can happen through a hidden attacker somewhere in the surrounding. Data protection is even worse in places with public access and on factory default WLAN access points without activated encryption. Standard Internet protocols as simple mail transport protocol (SMTP) messages are not encoded, thus all user data are transmitted in plaintext. Thus, sending an e-mail over an open access point has the same effect as broadcasting the content. With default firewall settings an intruder has access to local files, since the local subnet is usually placed inside the trusted zone. These examples emphasise that wireless links need some kind of traffic encryption.

When the first widespread digital cellular network was developed around 1985, standardisation of the global system for mobile communication (GSM) introduced the A5 cryptographic algorithms, which can nowadays be cracked in real-time (A5/2) or near real-time (A5/1). A further security threat is the lack of mutual authentication between the terminal and the network. Only the terminal is authenticated, the user has to trust the network unconditionally. In universal mobile telecommunications system (UMTS), strong encryption is applied on the radio part of the transmission and provides adequate security for current demands, but does not secure the transmission over the backbone. UTMS provides mutual authentication through an advanced mechanism for authentication and session key distribution, named authentication and key agreement (AKA).

Figure 1. A basic problem of broadcast environment



A LONG WAY TO SECURE COMMUNICATION

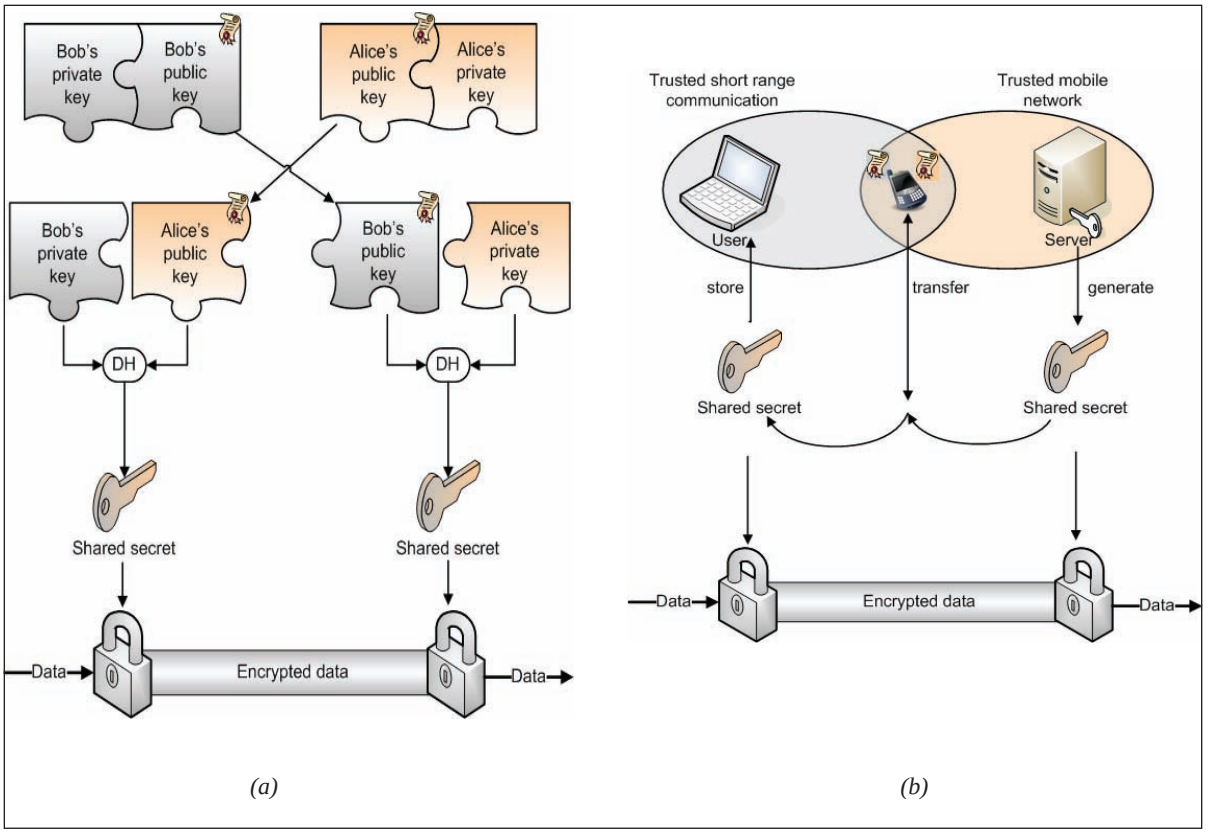
Applying some kind of cryptography does not imply a secured access. Communicating parties must negotiate the key used for encrypting the data. It should be obvious that the encryption key used for the communication session (session key) cannot be sent over the air in plaintext (see Figure 1).

In order to enable encryption even for the first message, several solutions exist. The simplest one, as used in cellular networks is a preshared key supplied to the mobile terminal on forehand. This key can be used later for initialising of the security infrastructure and can act as a master key in future authentications.

In more dynamic systems the use of preshared keys can be cumbersome. Most of WLAN encryption methods support this kind of key distribution. The key is taken to the new unit with some kind of out of band method, for example with an external unit, as indicated in Figure 2. Practically all private and many corporate WLANs use static keys, allowing an eavesdropper to catch huge amounts of traffic and thus enable easy decryption of the content. This implies that a system with just a secured access medium can be easily compromised. Non-aging keys can compromise even the strongest encryption, thus it is recommended to renew the keys from time to time.

Outside the telecom world it is harder to distribute keys on forehand, so key exchange protocols emerged, which offer protection from the first message and do not need any preshared secret. The most widespread protocol is the Diffie-Hell-

Figure 2. (a) Diffie-Hellmann key exchange and (b) out-of-band key delivery



man (DH) key exchange of Figure 2, which allows two parties that have no prior knowledge of each other to jointly establish a shared secret key over an insecure communications channel.

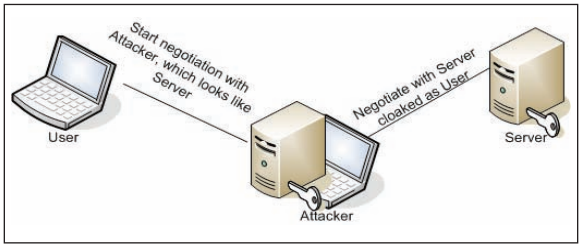
This protocol does not authenticate the nodes to each other, but enables the exchange data, which can be decoded only by the two parties. Malicious attackers may start a man-in-the-middle attack (see Figure 4). Since this problem is well-known, several modifications enable identity based DH, for example Boneh, Goh, and Boyen (2005) showed a hierarchical identity based encryption method, which is operating in fact as a public key system, where the public key is a used chosen string.

Public key infrastructure (PKI) can help defending corresponding parties against man-in-the-middle attacks. Public key cryptography is based on the non polynomial (NP) time problems, for example of factorisation or elliptic curves.

Two keys, a public and a private are generated. The public key can be sent in plaintext, because messages encrypted with the public key can only be decoded by the private key and vice versa. The two way nature of public keys makes it possible to authenticate users to each other, since signatures generated with the public key can be checked with the public key. Message authenticity can be guaranteed. Still, the identity of the node is not proven. The signature proves only that the message was encoded by the node, which has a public key of the entity we may want to communicate with.

Identity can be ensured by using certificates. Certificate authorities (CA) store public keys and after checking the owner's identity out of band, prove their identity by signing the public key and user information with their own keys. This method is required for financial transactions and business and government operations. Without a

Figure 3. Principle of a man-in-the-middle attack



CA, the public keys can be gathered into a PKI, which provides an exchange service. Here, most commonly, a method called web of trust is used. A number of nodes, who think that the key is authentic, submit their opinion by creating a signature. The solution enables community or personal key management, with a considerable level of authenticity protection.

While public keys can be sent, private keys must be kept secret. Although they are protected usually with an additional password, this is the weakest point in the system. If the user saves a key in a program in order to enter the key automatically, security provided by the system is equal to the security of the program's agent application. Private firewalls and operating system policies usually will not stop a good equipped intruder.

Another security issue for terminals is the lack of tamper resistant storage. Usage of smart cards is a solution to this issue, but introduces additional hardware requirements. The lack of secure storage is getting much attention in DRM schemes. Most DRM schemes use a software-based method, but also hardware-assisted ones have lately been introduced.

All these authentication methods, secure storage and rights management support secure data exchange, but they do not protect the privacy of user credentials, preferences, and profiles. Ad hoc networks, like personal area networks (PANs), which move around and are dynamically configured open for intrusion attacks on the privacy.

Thus, protection of user credentials in wireless environments is one of the focal points of current research. Before addressing privacy, we will first summarise issues in key management protocols.

FROM KEY EXCHANGE TO ACCESS CONTROL INFRASTRUCTURE

Mobility and wireless access introduced new problems in network and user management, as compared to fixed network installations with, for example, port-based access restrictions. The network operators want to protect the network against malicious intruders, charge the correct user for the use, and provide easy and open access to their valued services.

The first step to get access to an encrypted network is to negotiate the first session key. This has been solved in coordinated networks like mobile networks through pre-shared keys. Authentication and access control is provided by central entities to ensure operations.

In computer networks, which are not controlled in such way and usually not backed-up by a central authorisation, authentication, and accounting (AAA), different methods have been created for connection control. The basic method is still to negotiate encryption keys based on a preshared secret. Typical preshared keys are a password for hash calculation, one time password sent via cell phone or keys given on an USB stick.

There are several solutions to protect the data transmitted over a wireless link. In private networks, security based on preshared keys is a working solution. In corporate or public networks, a more robust solution is needed. The most promising way is to integrate session key negotiation into the AAA process. Since providers or companies have to identify the connected user, they rely on an AAA infrastructure and have an encryption of user credentials as compulsory policy. A certificate-based medium access control and AAA system is advised, where AAA messages can carry also the certificates needed to secure the message exchange.

As public key operations induce a lot of network traffic, the negotiated session keys have to be used in the most efficient way. Encryption protocols designed for wired environments, like transport layer security (TLS) do not consider problems associated with the broadcast transmissions and limitations of mobile devices. In a wired, or at

Figure 4. TLS key negotiation

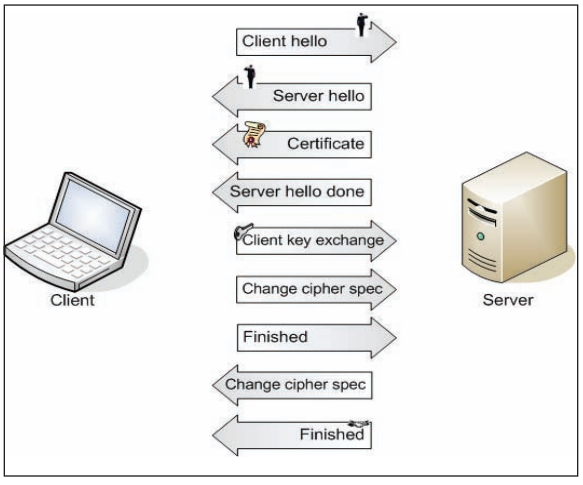
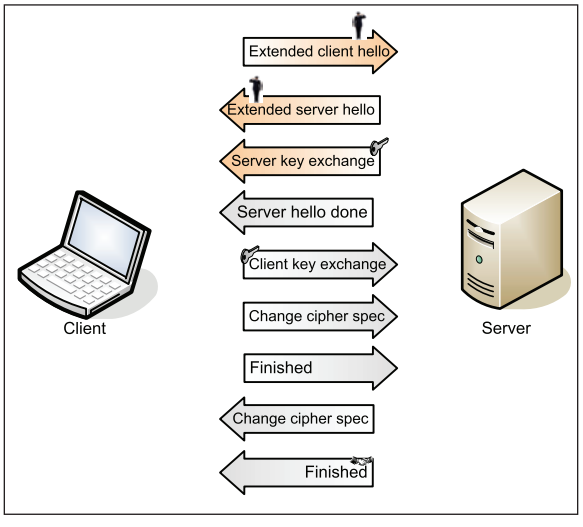


Figure 5. TLS-KEM key negotiation



least fixed environment, computational cost of key negotiations is usually neglected. For example TLS is using several public key operations to negotiate a session key. This can be a problem for mobile devices, since computational cost is much higher in asymmetric encryption. The standard TLS suite uses lots of cryptographic operations and generates a too large message load on wireless links (see Figure 5).

If a mobile device wants to execute mutual authentication with a service provider, with certificate exchanges, it can lead to big amounts of data transferred over the radio interface beside the high computing power needs.

In environments with limited resources, authentication and identity management based on preshared keys is still the most effective solution. Badra and Hajjeh (2006) propose an extension to TLS, which enables the use of preshared secrets instead the use of asymmetric encryption. This is in line with the efforts to keep resource needs at the required minimum level in mobile devices. A preshared key solution was also proposed by the 3rd Generation Partnership Projects (3GPP, 2004) and (3GPP2, 2007) as an authentication method for wireless LAN interworking. The problem with the proposed solution is preshared keys does not provide adequate secrecy nor identity protection in Internet connections. To deal with this problem, the TLS-key exchange method (TLS-KEM) provides identity protection, minimal resource need, and full compatibility with the original protocol suite as seen in Figure 6.

In direct comparison, the public key based TLS needs a lot more computing, data traffic, and deployment effort.

In UMTS networks, an array of authentication keys is sent to the mobile in authentication vectors. In the computer world a good solution would be using hash functions to calculate new session keys, as these consume low power and require little computing.

A moving terminal can experience a communication problem, as the overhead caused by key negotiation might extend the connection time to a network node. A preserved session key for use in the new network is a potential solution in a mobile environment, as it speeds up the node's authentication. Lee and Chung (2006) recommend a scheme, which enables to reuse of session keys. Based on the AAA infrastructure, it is possible to forward the key to the new corresponding AAA server on a protected network and use it for authentication without compromising system security. This can reduce the delay for connecting, and also reduces the possibility of authentication failure. Since the old session key can be used for authenticating the node towards the new AAA server, connection to the home AAA is not needed any more. The

messages are exchanged as follows (Lee & Chung, 2006): when sending the authorisation request to the new network, the node also includes the old network address it had. The foreign agent connects to the new local AAA server and sends an authentication request. The new AAA server connects to the old one sending a message to identify the user. The old AAA authenticates the message by checking the hash value included, and generates a nonce for the terminal and the foreign agent. The server composes an AAA-terminal answer, which is composed from a plain nonce, an encrypted nonce using the key shared between the old foreign agent and the terminal. Then the whole message is signed and encrypted with the key used between the two AAA servers. When the new AAA receives it, decrypts and sends the message to the new foreign agent. Based on the plain nonce, the agent generates the key and sends down the reply, which includes also the nonce encrypted by the old AAA. After the authentication of the user towards the network, the user can start using services.

Key distribution and efficiency in e-commerce applications is another important aspect. The network's AAA usually does not exchange information with third parties or can not use the authentication data of the network access because of privacy issues. Current security demands require mutual identification of communicating parties in an e-commerce application. This can easily lead to compromising the customer to companies (for example in a GSM network, the user has to trust the network unconditionally). If the user can also check the identity of the service provider, at least man-in-the-middle attacks are locked out.

When a user starts a new session with a service provider, this session should be based on a new key set. The session key has to be independent from the previous one in means of traceability and user identity should not be deductible from the session key, thus ensuring user privacy. For mutual identification, a key exchange method is proposed by Kwak, Oh, and Won (2006), which uses hash values to reduce resource need. The key calculation is based on random values generated by the parties, which ensures key freshness.

The use of hash functions is recommended in mobile environments, providing better performances for public key based mechanisms (Lim, Lim, & Chung, 2006). Mobile IPv4 uses symmetric keys and hashes by default. Since symmetric keys are hard to manage, a certificate-based key exchange was recommended, but this demands more resources. To lower the resource demand, a composite architecture was recommended (Sufatrio, 1999). The procedure uses certificates only in places where the terminal does not require processing of the public key algorithm and does not require storage of the certificate.

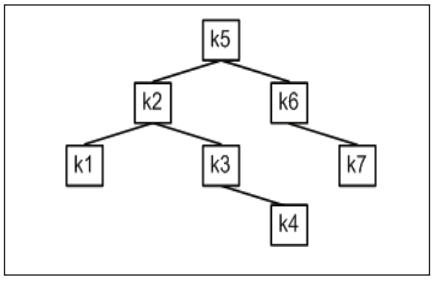
The result of the comparison shows that hash is by far the most efficient method in terms of key generation, but suffers from management difficulties. Lim et al. (2006) also demonstrates that a pure certificate-based authentication is unsuitable for mobile environments. Partial use of certificates and identity-based authentication with extensive use of hash functions can be a potential way ahead.

AUTHENTICATION OF DEVICE GROUPS

In a ubiquitous environment, moving networks appear. PANs and ad hoc connections based on various preferences emerge and fall apart. These devices communicate with each other and have usually very limited capabilities in terms of computing power and energy reserves. In order to provide secure communication between any part of the network, hierarchical key management methods emerged (Kim, Ahn, & Oh, 2006). Here a single trusted server is used to manage the group key. These entities are usually storing the keys in a binary tree, where nodes are the leaves.

Public key operations are usually required when a terminal wants to connect to a group for the first time. A group management system needs frequent key generation rounds, because it has to ensure forward and backward secrecy. Strict key management policies ensure that no new node is capable of decoding former traffic and none of the old nodes have the possibility to decrypt current traffic. To adjust resource usage to mobile environment, a management scheme which uses mainly simple operations like XOR and hash is advisable (Kim et al., 2006). As the key in the root of the

Figure 6. Keys in a binary tree



binary tree is used to authenticate the whole group, keys need to be regenerated when a node leaves the network. This procedure is starting from the parent of the former node and goes up to the root. Then the management unit sends out the new keys in one message. Building a tree from keys ensures fast searches and a simple, clean structure. In addition, all keys in the internal nodes are group keys for the leaves under them. So a subset of devices can be easily addressed.

The root unit has to compute these keys in acceptable time, requiring a more complex architecture. In PANs this is usually not a problem, but when a member of a larger subnet is leaving, calculations could be more demanding. A standard group key handling method is the Tree-based Group Diffie-Hellman (TGDH), where management steps assume that all nodes have the same processing capabilities. To ensure maximal efficiency, the highest performance unit shall be the one in the root of the tree (Hong & Lopez-Benitez, 2006). When node computing capabilities are showing big differences, the overhead caused by tree transformations does not represent a drawback.

Another significant group of devices that need encryption can be found in home networks, where the focus is on management of content and personal data.

SECURE HOME NETWORK AND RIGHTS MANAGEMENT

Deployment of wired or wireless home networks happens in roughly 80% of all households with broadband access (Noll, Ribeiro, & Thorsteinsson, 2005). Network-capable multimedia devices, media players, game consoles, and digital set-top boxes are widespread and part of the digital entertainment era. Content is stored within this network, and provided through the Internet to other users. Since the birth of peer-to-peer (P2P) networks, such technologies are in the crosshair of content providers. Recently, some software developers and a few musicians started using the torrent network for cost effective delivery of their content. A digital rights management method designed for such network is still missing.

Current right protection solutions are not compatible with each other and the user friendliness is also varying. The basic problem is, that just a very few devices are equipped with tamper resistant storage and integrated cryptographic capabilities. Beside software solutions, which are meant as weak solutions, hardware-based encryption can severely limit the lawful use of digital content. Recent lawsuits related to Sony's rootkit protection mechanism also reveals that customer rights of usage is considered to be more important than the legitimate wish of content providers to protect the content.

Trusted platform modules (TPM) are the most likely candidate for content protection in hardware-based solutions. While providing encryption capabilities, it is very likely that these components will be used to dispose the users' right to decide over the user's own resources.

The current discussions on DRM for audio content are regarded as minor when compared to high definition (HD) content protection. Even the connection to the screen has to use strong encryption, which has to exceed GSM/UMTS encryption in order to be acceptable for content providers. Enforcing a digital, end-to-end encrypted stream means that a HD-TV purchased at the end of 2006 may not work with the new encryption standards for HD. There is no current solution for computers to legally play full resolution HD. By the end of 2006 it was announced, that a workaround is arising to deal with the advanced content protection system of HD.

A more discrete, but not intrusive business model discussion for digital content management

is presented in order to visualise the requirements of this market. Apple's FairPlay enables making backup copies of audio tracks, which is permitted by law in several European countries, and copy of content between the user's iPod players. This solution is considered being to open for some content providers, and the distribution is limited to a server-client infrastructure. For HD content with high bandwidth needs such a server-client infrastructure is not advisable, both from a server and network point of view. The ever growing size of P2P networks form a perfect infrastructure to deliver content with high bandwidth need practically without substantial transmission costs. P2P networks are usually run without any DRM support. An additional infrastructure supporting DRM in a P2P network used to transmit content will enable high volume distribution of digital content (Pfeifer, Savage, Brazil, & Downes, 2006). If seamless license delivery and user privacy could be guaranteed, such a network could be the foundation of a low cost content delivery scheme.

While the usage of P2P networks is an excellent idea, the recommended solution proposed by Nützel and Beyer (2006) is similar to the Sony's rootkit solution: It bypasses the user control and is thus not acceptable. While the primary goal is to secure content, the software used in such solutions acts like hidden Trojans and opens backdoors not only for the content providers, but also other hackers.

Content usage across platforms is not supported yet, as a common standard does not exist. Pfeifer et al. (2006) suggests a common management platform for DRM keys with an XML-based, standard MPEG-REL framework. Users will also produce content with digital protection, in order to ensure that personal pictures cannot be distributed electronically. Social networks and groups of interest, as well as distribution of content in PANs is a challenge for DRM development. Zou, Thukral, and Ramamurthy (2006) and Popescu, Crispo, Tanenbaum, and Kamperman (2004) propose a key delivery architecture for device groups, which could be extended by a local license manager. The central key management unit could distribute licenses seamlessly to the device, which wants to get access, without invading user experience.

Kálmán and Noll (2006) recommend a phone-based solution. This represents a good trade-off between user experience and content protection. The phone is practically always online, most of them have Bluetooth or other short range radio transmitters, so licenses can be transmitted on demand. Since the phone has a screen and a keyboard, it is possible to request authorisation from the user before every significant message exchange, so the user can control the way licenses are distributes.

If we look aside the issues related to business aspects, computational issues still remain. Highly secure DRM entities will use asymmetric encryption and certificates. Sur and Rhee (2006) recommend a device authentication architecture, which eliminates traditional public key operations except the ones on the coordinator device. This is achieved by using hash chains including the permission, for example, a device can get keys to play a designated audio track ten times or permission to use five daily permits on demand. Such schemes allow end devices to be simpler and lower network communication overhead.

If a central device is not appreciated, a composite key management scheme may be used. The parties in the PAN will form a web of trust like in a confidentiality scheme, for example, pretty good privacy (PGP). In this web, the main key is split between nodes and cooperation is needed for significant operations. This means that if the scheme is operating on a (k, n) basis, k-1 nodes can be lost before the system needs to be generate a new key. Fu, He, and Li (2006) mention the problem of the PAN's ad hoc nature as the biggest problem. Since this scheme selects n nodes randomly, the ones that are moving between networks fast can cause instability in the system. Also, the resource need of this proposal is quite high on all nodes present.

When a scheme is enabling off-line use of license keys, attention should be given to problems arising from leaving or compromised nodes. Identity-based schemes become popular recently because of their efficiency in key distribution. The main drawback is that these proposals do not provide a solution for revocation and key renewal. Hoeper and Gong (2006) propose a solution based on a heuristic (z, m) method. The solution is similar

to the threshold scheme shown before, but enables key revocation. If *z* nodes are accusing one node to be compromised, based on their own opinion, the node is forced to negotiate a new key. If a node reaches a threshold in number of regenerations in a time period, it could be locked out, since most likely an intruder is trying to get into the system or the internal security of the node is not good enough. The assumptions about the system are strongly limiting the effectiveness of the solution. The most stringent assumption is that they require to nodes to be in promiscuous mode. This can lead to serious energy problems. Another requirement is that there has to be a unit for out-of-band key distribution. This unit could be the cellular phone.

SMART CARDS AND CELLULAR OPERATORS

The use of smart cards has its roots in the basic problem of security infrastructures: even the most well designed system is vulnerable to weak passwords. A card, which represents a physical entity, can be much easier protected compared to a theoretical possession of a password. Smart cards integrate tamper resistant storage and cryptographic functions. They are usually initialised with a preshared key and creating a hash chain, where values can be used as authentication tokens.

The remote authentication server is using the same function to calculate the next member. The encryption key is the selection of a collision resistant hash function. While the tokens they provide are quite secure, a problem with smart cards is that they represent a new unit that has to be present in order to enable secure communication, and user terminals must be equipped with suitable readers. The additional hardware does not only cause interoperability problems, but is usually slow, as a measurement conducted shows (Badra & Hajjeh, 2006). This becomes eminent when high traffic is associated with asymmetric encryption; sending a "hello" message with standard TLS to the smart card needed 10 seconds. In contrast, the modified TLS-KEM needed 1.5 s.

A user-friendly, seamless key delivery system can be created with the help of cellular operators and SIM cards with enhanced encryption capabilities. The SIM and USIM modules used in GSM/UMTS are quite capable smart cards. They offer protected storage with the possibility of over the air key management, good user interface, and standard architecture. Danzeisen, Braun, Rodellar, and Winiker (2006) shows the possible use of the mobile operator as trusted third party for exchanging encryption keys out of band for other networks.

Delivery of the mobile phone key to a different device can be problematic, since most devices do not have a SIM reader, or it is inconvenient to move the SIM card from the mobile phone to another device. New developments in near field communication may overcome this and enable short range secure key transfer.

BREAKING THE LAST CENTIMETRE BOUNDARY

Frequency of authentication request is a key factor in user acceptance. If a system asks permanently for new passwords or new values from the smart card hash chain, it will not be accepted by the user. On the other hand, if a device gets stolen and it asks for a password only when it is switched on, then a malicious person can impersonate the user for a long time. A potential solution is to create a wearable token with some kind of wireless transmission technology and define the device behaviour such that if the token is not accessible, it should disable itself in the very moment of notification.

Since the main challenge is not securing data transfer between the terminal and the network, but to authenticate the current user of the terminal, a personal token has to be presented. As proposed by Kálmán and Noll (2007), the mobile phone can be a perfect personal authentication token if it is extended by a wireless protocol for key distribution.

With the capabilities of user interaction, network control of the mobile phone, it can be ensured that critical operations will need user presence by requiring PINs or passwords. Possible candidates for key exchange are Bluetooth

(BT), radio frequency identification (RFID), and Near Field Communications (NFC). NFC is a successor of RFID technology in very short range transmissions. BT is close to the usability limit, since its transmit range reaches several meters. But the two later ones are promising candidates. Depending on the frequency, general RFID has a range of several meters while NFC operates in the 0-10 cm range. NFC is recommended, as the range alone limits the possibilities of eavesdroppers and intruders who want to impersonate the token while it is absent. The use of repeaters in the case of NFC, a so-called wormhole attack as described by Nicholson, Corner, and Noble (2006), looks not feasible because of the tight net of repeaters required. Also, the capability of user interaction provides an additional level of security.

Mobile phones with integrated NFC functionality are already available and serve as user authentication devices. To use these devices as tokens for other terminals, they have to be placed very close to each other. This prevents accidental use in most cases. To check presence of the token, heartbeat messages might be introduced. By design, this solution is very capable of distributing preshared keys for other devices out of band. Meaning, the phone can get the keys from the cellular network from an identity provider and send it down to the appropriate device by asking the user to put the devices close to each other for a second or two.

Transmission of the key must be done only when needed, so the programmable chip on the phones has to be in a secured state by default and only activated by the user's interaction. Protection of RFID tags is shown by Rieback, Gaydadjiev, Crispo, Hofman, and Tanenbaum (2006), where a proprietary hardware solution is presented. In case of a phone-based NFC key transmission, additional active devices might be unnecessary to use, but for general privacy protection, IDs with RFID extensions must be treated with care.

Transmission of certificates would not need additional encryption over the NFC interface, while other keys may require a preshared key between the phone and the terminals, which can be done via a wired method or by the phone provider. Most providers have at least one secret key stored on phones and a public key connected to that one. Based on this, DH key exchange would be possible between terminals and the phone using the cellular network as a gateway. An NFC-enabled phone could be the central element of a home DRM service, as it is online, capable of over the air downloads, and still able to ensure user control.

ON THE DAWN ON PERSONAL CONTENT MANAGEMENT

From the viewpoint of secure data transmission and user authentication, access and distribution of digital content can be ensured. Open issues remain for moving PANs and devices with limited capability. Focus nowadays is on protecting the user's privacy. As usage of digital devices with personal information was limited, user privacy was not of primary concern for a long time. Since PANs and home networks hold a large amount of critical personal data, this has to change (Jeong, Chung, & Choo, 2006; Ren, Lou, Kim, & Deng, 2006).

In a ubiquitous environment users want to access their content wherever they are. This has to be enabled in a secure manner. With upcoming social services, also fine grained access control methods have to be deployed inside the personal infrastructure. The focus of DRM research has to shift towards the end user, who will also require the right to protect himself/herself and his/her content with the same strength as companies do.

Extending the phone's functions may be problematic because of energy consumption and limited computing power. This could be easily solved by the technology itself, since a new generation of mobile terminals is arriving every half year. The capacity and functionalities of the SIM cards will be extended, the newest 3GPP proposals are predicting high capacity and extended cryptographic possibilities.

Regarding legal aspects, extending the SIM possibilities may cause some concern, since the SIM cards are currently owned by the network operators.

CONCLUSION

Transport encryption and authentication of devices has been the subject of research for a long time and resulted in sufficient secure solutions with current technologies. The focus in recent proposals is on the limited possibilities of mobile terminals and adoption of encryption technologies for mobile and wireless links.

Distributing keys between nodes is solved, except for the first step, which usually requires out-of-band transmissions. A solution for this initial key distribution might be the mobile phone with its integrated smart card and already existing communication possibility. As phones come with NFC, they may act as contact-less cards to distribute keys between devices.

While device authentication is handled sufficiently, user identity is hard to prove. A knowledge-based password or PIN request is not a user-friendly solution. Current proposals tend to be insecure when performing the trade-off between user experience and security.

Focus on research should be paid towards personal area and home networks. These networks hold most of the user's personal private data and content, either purchased or created by the user. Currently no standard solution exists for managing content rights or for access control of own content.

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KEY TERMS

Diffie-Hellman Key Exchange: Diffie-Hellman key exchange is a procedure, which allows negotiating a secure session key between parties, who do not have any former information about each other. The negotiation messages are in band, but because of the non-polynomial (NP) problem used in the procedure, adversaries are not able to compromise it.

Mutual Authentication: Mutual authentication occurs when the communicating parties can mutually check each others identity, thus reducing

the possibility of a man-in-the-middle attack or other integrity attacks.

Out of Band Key Delivery: Out of band key delivery occurs when an encryption key is delivered with a mean, which is inaccessible from inside the network it will be used in. An example is to carry a key on an USB stick between parties, where the key will never be transmitted over the network.

Rootkit: Rootkit is a kind of software to hide other programs. Mainly used by Trojans, they enable hidden applications to access local resources without user knowledge.

Seamless Authentication: Seamless authentication is a method where the user is authenticated towards an entity without the burden of credential requests. For high security requirements, transparent methods are not applicable, but can provide additional security in traditional username/password or PIN-based sessions.

Session Key: Session key is a short life, randomly generated encryption key to protect one or a group of messages. The main purpose is to use expensive encryption operations only when starting a session and use a simpler to manage cipher in the later part.

Chapter XII
Architecture and Protocols for Authentication, Authorization, and Accounting in the Future Wireless Communications Networks

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ABSTRACT

The architecture, and protocols for authentication, authorization, and accounting (AAA) are one of the most important design considerations in third generation (3G)/fourth generation (4G) telecommunication networks. Many advances have been made to exploit the benefits of the current systems based on the protocol remote authentication dial in user service (RADIUS)protocol, and the evolution to migrate into the more secure, robust, and scalable protocol Diameter. Diameter is the protocol of choice for the IP multimedia subsystem (IMS) architecture, the core technology for the next generation networks. It is envisioned that Diameter will be widely used in various wired and wireless systems to facilitate robust and seamless AAA. In this chapter, we provide an overview of the major AAA protocols RADIUS and Diameter, and we discuss their roles in practical 1xEV-DO network architectures in the three major network tiers: access, distribution, and core. We conclude the chapter with a short summary of the current and future trends related to the Diameter-based AAA systems.

INTRODUCTION

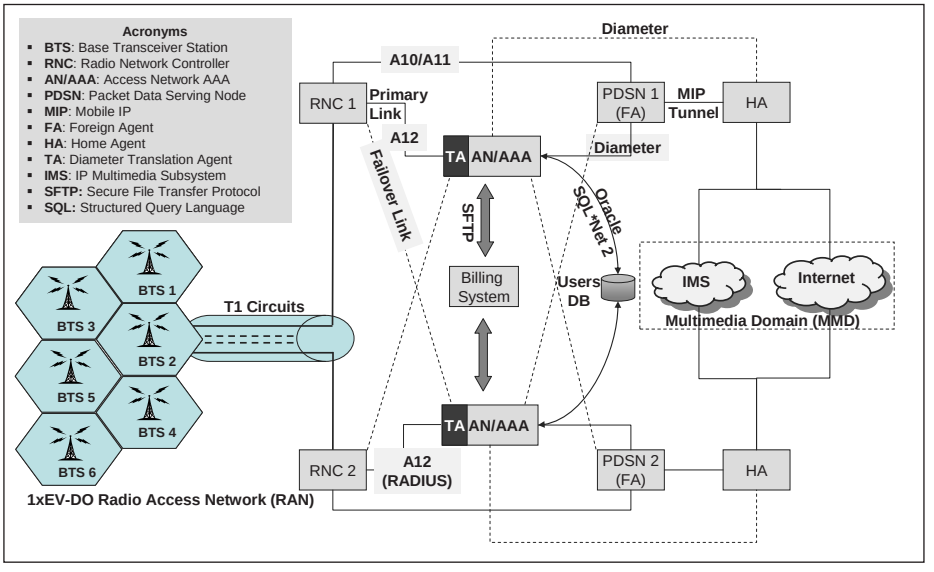
Many 3G cellular providers consider the architecture for the authentication, authorization, and accounting (AAA) system as one of the most important functional blocks for the success of service delivery. Typically, users are authenticated when requesting a service and only after successful authentication they are authorized to use the service. Once the user is granted access to the service, the network generates accounting messages based on the user's activity. Currently, the remote authentication dial in user service (RADIUS) protocol is the most widely deployed protocol in cellular networks to perform subscriber AAA. Since RADIUS is susceptible to various security threats, a standard developed by the Internet Engineering Task Force (IETF), called Diameter, was proposed to substitute RADIUS in the future. Unlike its predecessor RADIUS, Diameter offers reliable and secure communication enabling seamless roaming among operators and support of auditability, capability negotiation, and peer discovery and configuration. Diameter augments its reliable transmission capabilities by defining failover mechanisms and thus embraces two crucial elements for the robust communication of sensitive billing and authentication messages. Since most of the current equipment and radio standards only support RADIUS for authentication, it is evident that cellular network operators will be running both protocols in the near future. Therefore, it can not be sufficiently emphasized that prudent decisions need to be made when designing AAA systems with multiple protocols in mind at the three major tiers: access, distribution, and core.

The purpose of this chapter is to address the specific aspects of the AAA system architecture of these three major tiers. Given the broadness of the scope and the myriad of the existing AAA standards, we sharpen our focus on a reference 3G cellular network architecture which we define and show in Figure 1. As can be seen from Figure 1, a typical AAA system in 3G architectures is characterized by three distinctive architectural elements: (1) radio access network (RAN), (2) distribution network based on mobile IP (MIP), and (3) a multimedia domain (MMD)[1] based core including both IP multimedia system (IMS) networks and Internet access deployments. The RAN, based on one of the 1x carrier evolution data only (1xEV-DO) standards/revisions for wireless transmission, consists of various base stations (BSs) and radio network controllers (RNCs). The distribution network consists of the MIP elements, that is, the packet data serving node (PDSN) playing the foreign agent's (FA) role and the home agent (HA). It is worth observing that this architecture has a hierarchical nature, where multiple BTSs are governed by a single RNC and multiple RNCs are covered by a single PDSN region. Finally, at the core, we have the IMS elements, including it standardized elements such as the call session control functions (CSCF) and home subscriber servers (HSS) enabling robust applications and services such as gaming, presence, voice over IP (VoIP), and so forth.

Upon receiving a mobile subscriber call, the RNC authenticates the subscriber's request by communicating with the access network AAA (AN-AAA) over the RADIUS-based A12 interface. Once authenticated, the RNC contacts the PDSNs through the A10/A11 interface (3rd Generation Partnership Project 2 [3GPP2] A.S0008-B, 2006). Note that since the A12 interface is RADIUS based, a translation agent (TA) needs to be used to translate the RADIUS requests to Diameter for authentication. In Figure 1, we illustrate that the AAA contacts an Oracle-based users' database to authenticate the incoming calls. We assume that the TA, AAA, and the AN-AAA are collocated in the same physical platform for simplicity. For higher reliability, RNCs usually connect to multiple AAAs (one primary and another secondary AAAs) to allow redundancy to admit users into the system in case of AN-AAA connectivity problems.

Once admitted, the mobile node (MN) starts a point-to-point (PPP) session with the PDSN. During the process of PPP establishment, the PDSN advertises itself as a MobileIP FA and challenges the user. The user then replies with a Mobile IP registration request that answers the PDSN's challenge. The PDSN forwards this information to the AAA. The AAA validates the user's response

Figure 1. A 1xEV-DO reference network architecture



based on the MN-AAA shared secret and responds to the PDSN. In case of successful authentication, the PDSN proceeds with the MobileIP registration process with the HA and establishes a MobileIP tunnel to serve the user's traffic. At this point, the PDSN starts to generate accounting towards the AAA server to reflect the subscriber's usage. Accounting data is reformatted and is communicated to the upstream billing systems for further processing. Here, we assume simple secure FTP (SFTP) communication. Note that the PDSN also connects to multiple AAA's for redundancy purposes. In our illustrative architecture, the PDSN implements the Diameter MobileIP application and thus needs no translation functionality.

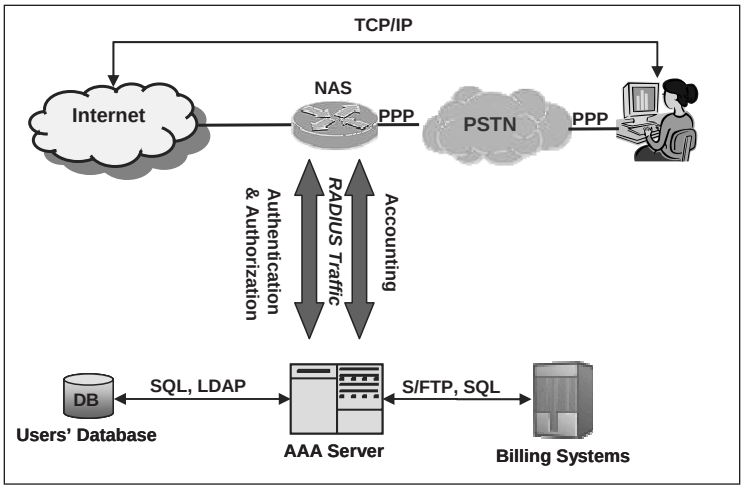
In this illustrative reference architecture, RADIUS is deployed in the access tier and translation agents were utilized to convert between RADIUS and Diameter, while Diameter applications at the distribution and network tiers were natively supported. Following this example, we organize the chapter as follows. First, we present the AAA concept and quickly survey RADIUS and its current deployment features. Then, we discuss the evolution from RADIUS to Diameter and shortly review the current Diameter standard. Afterwards, we illustrate a prospective end-to-end application of Diameter at all the three major network tiers in the wireless network, including access, distribution, and core. Finally, we summarize the chapter and discuss open issues and future work.

BACKGROUND

The RADIUS Protocol

AAA systems received significant attention from network service providers throughout the past decade. The need for a standardized, simple, and scalable protocol that accomplishes the required AAA functionality was the main motivation for the introduction of the (RADIUS) protocol (Rigney, 2000; Rigney Willens, Rubens, & Simpson, 2000; RFC2866). In 1998, RADIUS was the only protocol that seemed to satisfy the IETF NASREQ working group's requirements for authentication and authorization (Rigney, 1998). Due to its wide implementation by many networking equipment vendors, its simplicity and scalability, it became the protocol of choice for many service providers. RADIUS was quickly extended to support various networking protocols such as MobileIP (Perkins, 2002), IP security (IPsec) (Kent & Seo, 2005), and the IEEE 802.1x authentication.

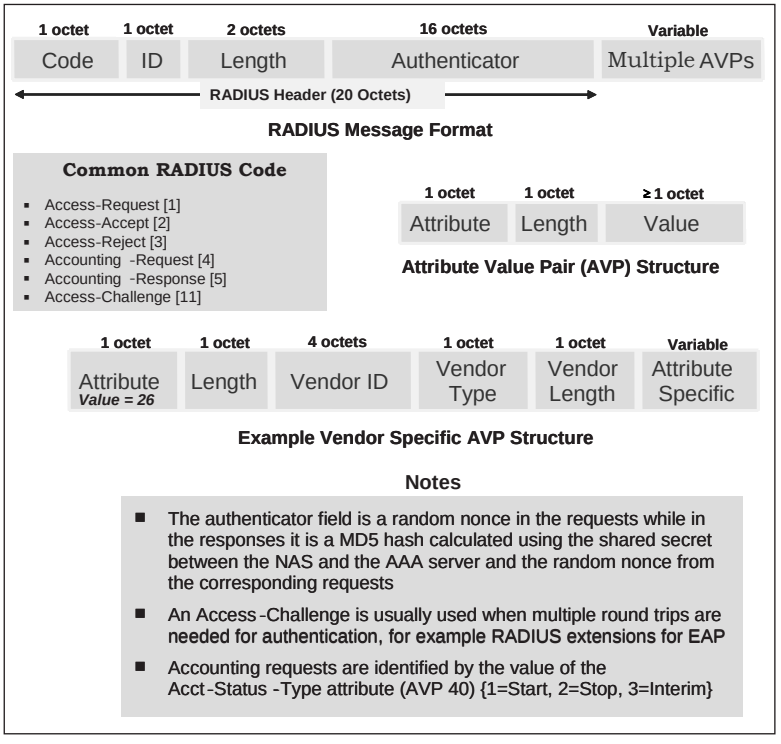
Figure 2. A simple service provider's architecture with AAA functionality



In RADIUS, after the user is granted access, the network access server (NAS) generates accounting messages based on the user's activity. The NAS is usually the gateway to the IP network. Routers, WiFi access points (APs), PDSNs, and gateway general packet radio service (GPRS) support nodes (GGSN) in GPRS networks, are typical examples of NASs in telecom networks. As shown in Figure 2, a user tries to access the Internet through a dialup modem connection. The PPP protocol is mainly used to establish the communication between the user and the NAS, that is, the router in this example. The NAS attempts to authenticate the user either through the password authentication protocol (PAP) or the challenge handshake authentication protocol (CHAP). Upon obtaining the responses from the client, the NAS generates an Access-Request and sends it to the RADIUS server in order to validate the user's responses. Typically, the RADIUS server is connected to an external database that contains the user's credentials and authorized services. Thus, the RADIUS server returns an Access-Accept message if the user credentials are valid, otherwise it returns an Access-Reject. The Access-Accept message may contain authorization information. For example, an Access-Accept message may contain: filters to grant the user access to internal networks, specific routing instructions to the NAS, quality of service (QoS) settings, and so forth. This authorization set is returned as a group of attribute value pairs (AVP) in the Access-Accept message.[2] Once the user is granted access, the NAS generates accounting messages based on user's activity (connection time, total bytes used, etc).

The RADIUS message format is shown in Figure 3. It consists of a 20 octet header followed by multiple AVPs. AVPs include standardized types and values. For example, the username is passed to the AAA server using the *User-Name* attribute. To allow expandability, the AVP type 26 is reserved for vendor-specific AVPs (VSAs). Thus, a vendor requests a *Vendor ID* from the Internet Assigned Numbers Authority (IANA) to be able to define specific attributes for his equipment. The following are sample vendor ID values: Cisco (9), Nortel (2637), 3GPP (10415), and 3GPP2 (5535). Usually, AAA implementations include dictionary files that define the AVP type and the expected values, for example refer to Braunöder (2003). RADIUS accounting is composed of three primary message types: (1) *Accounting-Start*, (2) *Accounting-Interim*, and (3) *Accounting-Stop*. Accounting messages usually carry the user's session information. For example, in CDMA2000-based systems accounting messages may contain the user's assigned IP address; user's sent and received byte counts; user's electronic serial number; calling and called station numbers; accounting session ID; BS ID; and so forth, (3GPP2 A.S0008-B, 2006; 3GPP2 X.S0011-005-C, 2006). Note that the electronic serial number and the BS ID attributes are 3GPP2 VSAs augmented to the standard RADIUS AVPs.

Figure 3. RADIUS message format



RADIUS offers reliability over the intrinsically unreliable user datagram protocol (UDP)[3] by requiring a response for each request. If a response is not received within a predefined time period (TO), the request times out. It is then up to the requestor (RADIUS client) to either retry the same server, another RADIUS server, or even drop the request. The timeout value and the maximum number of allowed retransmissions are configurable parameters at the client. It is noteworthy to mention that the failover mechanism was not standardized in RADIUS and often raised interoperability issues due to the inherent differences in the AAA implementations (Calhoun, Loughney, Guttman, Zorn, & Arkko, 2003).

RADIUS follows a client/server model where clients maybe NASs or other RADIUS servers. RADIUS clients and servers share a common secret to secure their communications. This method is weak and is only intended to secure communication within a trusted network.[4] Sometimes an AAA server serves as a RADIUS client/proxy when it is provisioned with a policy instructing it to forward the request to another RADIUS server. Such policies are occasionally based on the domain in the user's network access identifier (NAI). Standards (Aboba & Vollbrecht, 1999) refer to this setup as the proxy-chain configuration. For instance, in a roaming scenario the host AAA is usually configured to forward AAA requests from the hosting NAS to the home AAA. Note that multiple proxies maybe traversed along the path to the home AAA server as shown in Figure 4.

Evolution from RADIUS to Diameter

Diameter Protocol Overview

As network architectures evolved and with the tremendous growth in the wireless data infrastructures, secure inter-domain communication among various AAA servers to exchange subscribers' credentials, profiles, and accounting information became an absolute necessity. Despite its tremendous success, RADIUS inherent security vulnerabilities, its questionable transport reli-

Figure 4. Proxy chain configuration

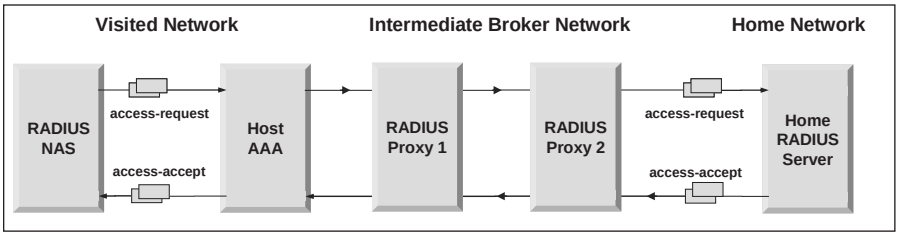
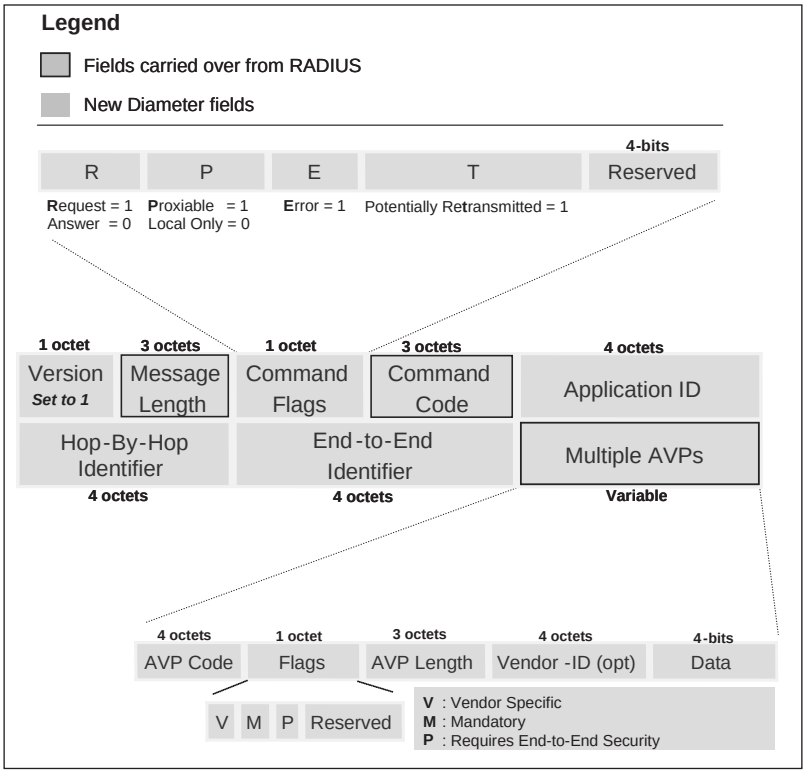


Figure 5. Diameter protocol



ability, and its limited redundancy support were the primary reasons for the introduction of the Diameter protocol (Calhoun et al., 2003) as a substitute protocol. Diameter was carefully designed to address security and reliability while thoroughly exploiting the benefits of RADIUS. Thus, secure transmission mechanisms using a choice of IPsec or transport layer security (TLS) protocols were integrated into Diameter, while reliable transport was enhanced by designing Diameter to run over either stream control transmission protocol (SCTP) or transmission control protocol (TCP) supported by standardized failover and failback (recovery) mechanisms.

Diameter RFC reused many of the RADIUS message codes and attributes and extended them. Figure 5 shows Diameter's header format. The framed fields in Figure 5 are those carried over from RADIUS. In contrast to RADIUS, note the introduction of the Version, Command Flags, Application ID, Hop-By-Hop ID, and End-to-End ID fields in Diameter. Also note the increase in size of the message length field (from 2 octets in RADIUS to 3 in Diameter). Note also that the authenticator

field is no longer present as security is guaranteed by the integrated IPsec and TLS protocols. Command codes in Diameter start from 257 to maintain compatibility with RADIUS. Unlike in RADIUS, the requests and answers have the same command codes in Diameter, for example, the accounting request (ACR) and answer (ACA) commands have the command-code of 271. Diameter nodes can recognize message types (e.g., whether it is ACA or ACR) based on the "R" flag in the command flags shown in Figure 5. The "P" flag instructs nodes whether a message must be processed locally and should not be forwarded. The "E" flag along with the result-code AVP is used to indicate errors (and possibly redirection as we will see later). Finally, the "T" flag is used to indicate a possible duplication in case of retransmissions after a failover. Figure 5 also shows Diameter's AVP structure. The most significant addition is the inclusion of the flags field.

Diameter Agents

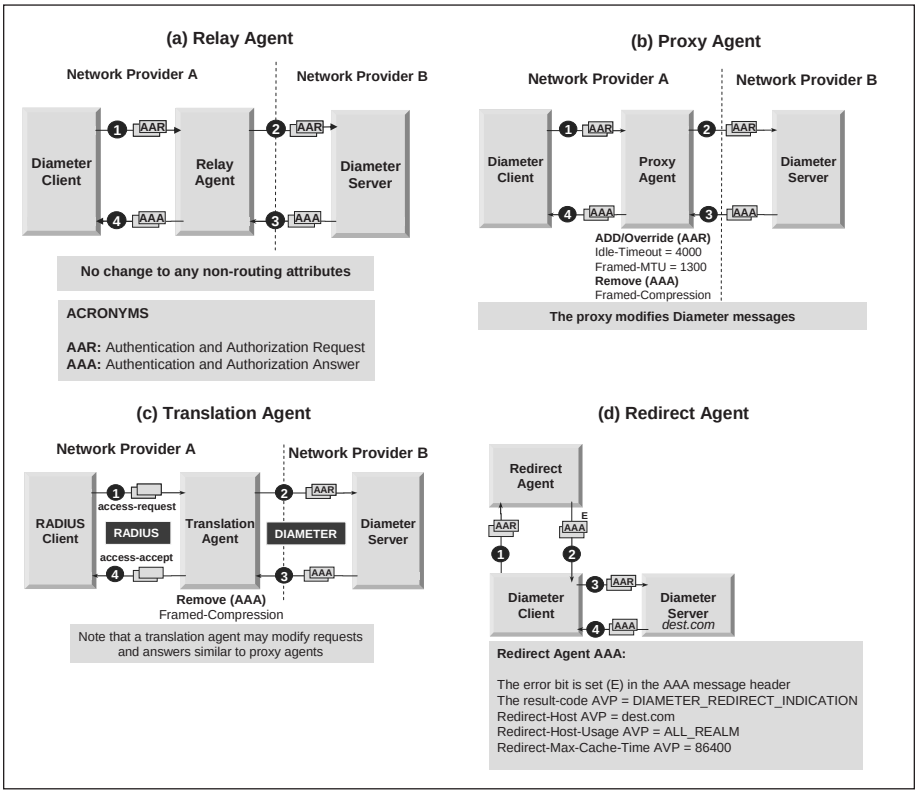
To facilitate migration from the current RADIUS infrastructure, Diameter offers indirect backward compatibility by introducing translation agents to convert RADIUS messages into Diameter messages and vice versa. Besides the main incentive of reusing as much of the RADIUS codes and attributes as possible for simpler migration, such reuse is also beneficial in reducing the amount of processing on the translation agents. Diameter supports a broader definition of scalability to suite roaming scenarios by including relay and redirect agents while still maintaining the RADIUS proxy agent model, therefore allowing the deployment of different architectures.

A proxy agent is used to forward Diameter traffic to another Diameter peer in order to handle the request. The decision to forward requests is policy based as in RADIUS. Proxy agents may modify packets and may originate rejection messages in case of policy violation, for example, in case of receiving requests from unknown realms. On the other hand, relay agents only forward requests without modifying any of the non-routing attributes. Relays and proxies are required to append the route-record AVP with the identity of the peer it received the request from prior to forwarding it. The reader is encouraged to refer to Calhoun et al. (2003) for more information on routing AVPs and their usage. Finally redirect agents, as their name implies, are used to refer clients to alternative AAAs. Redirect agents may act as proxies or end servers for other requests. For example, an AAA server may handle the Diameter base accounting messages while redirecting requests that require Diameter server support for MobileIP. Figure 6 summarizes the functionality of Diameter agents and illustrates the message flow in order of transmission. In Figure 6a, the relay agent only forwards the Diameter *Authentication and Authorization Request* (AAR) to Provider's B Diameter server. In Figure 6b, the proxy agent has an outbound policy for AAR to add or override the session Idle-Timeout attribute to 4,000 seconds and maximum link MTU to 1,300 bytes. It is also configured with an inbound policy for the *Authentication and Authorization Answers* (AAA) to remove any instructions for compression. Figure 6c shows the translation agent's role. Note that a translation agent may at the same time act as a proxy, that is, add, modify, or remove AVPs while converting between RADIUS and Diameter. Finally, as shown in Figure 6d, the Diameter client issues an AAR towards the redirect agent. Once received, the redirect agent sends back an AAA with the "E" flag set with the result-code AVP set to DIAMETER_REDIRECT_INDICATION instructing the Diameter client to contact *dest.com* by using the Redirect-Host AVP. A redirect agent may also provide indication on the usage of the redirect instruction, that is, whether its response is meant for all realms or simply restricted for the request's realm, whether the redirection policy should be cached at the requestor (Client), and for how long, and so forth.

Server Initiated Messages in Diameter

Unlike RADIUS, Diameter is a peer-to-peer protocol where any Diameter node may act as a client or server at any time. Peers are simply the next hop nodes that a Diameter node communicates with. A significant improvement over RADIUS is that Diameter has mandatory support of server-initiated messages to allow operations like re-authentication

Figure 6. Diameter agents' operation



and network triggered session abortion. Diameter outlines a policy based framework for end-to-end security[5] and establishes auditability and proof of agreement by mandating message path authorization in case a message traverses multiple Diameter agents between two providers. This is accomplished by mandating authentication and authorization for each Diameter node along the path between two Diameter end-nodes. For instance, a service level agreement (SLA) among providers A, B, and C prevents the intermediary provider C from passing A and B's accounting traffic through the untrusted network U. Here, Diameter offers path authorization by requiring that each Diameter agent (provider C in this example) append the identity of the peer the request is received from prior to forwarding it. The Diameter servers must validate the conformance of the route-record attributes with the service policy. Thus, if servers on A or B detect entries for any untrusted servers, an AUTHORIZATION_REJECT error message is sent.

Diameter Applications

So far, we have only presented a summary of the so-called Diameter-based protocol, which must be implemented by every Diameter node. One of the most powerful features in Diameter is the introduction of the so-called "Diameter Applications." A node's capability to support certain applications is exchanged upon connection setup in the so-called Diameter capability exchange request and answer (CER, CEA) messages (Calhoun et al., 2003). Note that although many extensions were also added to RADIUS to support different applications (e.g., the Extensible Authentication Protocol [EAP], for WiFi in Rigney, 2000), RADIUS does not include any mechanisms to inform clients whether servers support such extensions. In other words, there is no standardized method to allow clients to discover whether the EAP extension is supported on an arbitrary server. This problem was solved in

Diameter by introducing the concept of Diameter applications.

It is important to understand that RFC 3588 defines the minimum prerequisites for a Diameter node implementation and maybe used by itself only for accounting. In case of authentication and authorization, a Diameter node must implement a specific application. The most common applications are Diameter NAS (Calhoun, Zorn, Spence, & Mitton, 2005) and MobileIPv4 (Calhoun, Johansson, Perkins, Hiller, & McCann, 2005). The Diameter NAS application defines NAS-related requirements where PPP-based authentication/authorization is needed. Diameter MobileIPv4 application defines AAA functionality in scenarios where users roam into foreign provider networks. The concept of Diameter applications was employed in many areas, and the following is a summary of three major Diameter applications,

- Diameter credit control application (Hakala, Mattila, Koskinen, Stura, & Loughney, 2005) is proposed to handle online billing for prepaid solutions. Prepaid billing implies real-time rating for the requested service, user's balance validation, and service suspension once the user's account is exhausted. Debiting and crediting are also supported for some applications such as gaming. Note that Diameter accounting defined in Calhoun et al. (2003) is mostly suitable for postpaid services where off-line processing of accounting records is performed.
- Diameter EAP (Eronen, Hiller, & Zorn, 2005) is used to support end-to-end authentication in dial-up, 802.1x, 802.11i, and in IPsec IKEv2. It eliminates the possibility of man-in-the-middle attacks if node is compromised within a proxy chain.
- The Diameter Session Initiation Protocol (SIP) application (Garcia-Martin, Belinchon, Pallares-Lopez, Canales-Valenzuela, & Tammi, 2006) supports HTTP digest authentication (RFC2617) mandated by SIP (Rosenberg et al., 2002) to allow SIP user agents and proxies to authenticate and authorize user's requests to access certain resources. This application does not depend on the Diameter NAS nor MobileIPv4 applications, where as it supports the Diameter credit control application but does not depend on it. Moreover, Diameter SIP allows locating SIP servers when a SIP agent requests routing information. Finally, it provides a mechanism for pushing updated user profiles to the serving SIP server in case the profile is (administratively) updated.

Finally, it is extremely important to understand that Diameter applications need to be defined only when none of the existing Diameter applications can support the required message flow without major modifications. Such major changes include adding new mandatory AVPs, commands requiring different message flows from any of the currently defined applications, or requiring support for new authentication methods with new AVPs (Fajardo & Ohba, 2006).

Protocol Mechanisms

Diameter Peer Discovery

Diameter offers three primary means to discover Diameter peers: static, Service Location Protocol Version 2 (SLPv2) queries, and domain name system. Thus, a *peer table* entry is created after peer discovery is executed. Note that peer discovery maybe triggered upon the reception of a CER. In some cases, policies may allow establishing connections with unknown peers. In this case, the peer table entry is built from the peer's identity in the CER and expires as soon as the connection is closed. In most of the cases, peer table entries for known peers are created along with their advertised applications. Thus, only requests for advertised applications are forwarded to these peers.

Diameter Policies

Routing tables provide guidance to the Diameter node on how to process a received request. Figure 7 illustrates an example realm routing table for Relay/Proxy Agent. Note that a policy includes a realm, an application identifier, and an action. When forwarding is needed, the next hop server is given and whether the route entry was statically or dynamically discovered (through a redirect, for example), along with its expiration time. The

Figure 7. Sample routing policy

```
RealmName=ourrealm.com AND destination=ourid,
ApplicationID=any, Action=LOCAL

RealmName=myMIPdomain.com, ApplicationID=MobileIPv4,
Action=REDIRECT, Next-Hop=ServerMIP.com,
Dynamic:ExpirationTime=900

RealmName=myMIPdomain.com, ApplicationID=DiameterNAS,
Action=PROXY, Next-Hop=ServerACT.com, Static, Proxy_Policy =
{outbound[Idle-Timeout=400],inbound[remove framed-compression]}

DefaultPolicy –Answer result-code=DIAMETER_UNABLE_TO_DELIVER
```

default policy in case no route is available is to return an error message with the DIAMETER_UNABLE_TO_DELIVER result code.

Diameter Request Routing

Diameter request routing refers to the process needed when originating, sending, and receiving requests. When originating a request, the Diameter node sets the Application-ID, the Origin-Host and Origin-Realm AVPs along with the Destination-Host and/or realm. When receiving a message, the node checks the route-record AVP to make sure that there are no routing loops.[6] It also checks whether it is the ultimate destination of the message. If not, the node acts as an agent and according to its policy it relays, proxies, or redirects the message. Each forwarded (i.e., proxied[7] or relayed) message is updated with a locally generated hop-by-hop identifier. This field is used to match requests and answers. Answers are routed opposite to how requests are routed and using the hop-by-hop identifiers the expected answers at each hop are recognized. Using the hop-by-hop identifier and the saved sender's information, the answer is forwarded back to the previous node with the hop-by-hop identifier restored to its original value. This process ends once a node finds its identity in the origin-host.

Diameter's Failover and Failback Algorithms

Diameter implements the so-called watchdog algorithm to detect communication trouble and initiate the failover mechanism. A Diameter node may have a primary server and multiple secondary servers for redundancy. When a communication problem is detected, a secondary server is promoted to primary and the primary is suspended. Notice that this is important to guarantee consistent failover for all requests.

The link is considered responsive as long as acknowledgements arrive. If the link is idle for "tw" seconds then a device watchdog request (DWR) is sent. If no device watchdog answer (DWA) arrives in "tw" seconds, the primary is suspended, the secondary server is promoted, and all subsequent communication is sent to the promoted server. Note that outstanding messages maybe sent on the failover link and in this case the "T" flag is set in each message to indicate (to the end server) that such messages maybe duplicates. If another "tw" seconds pass without receiving the DWA on the suspended primary link, then the transport connection is closed. The connection may be retried periodically, but for reopened connections, a connection validation procedure must be initiated. In this case, three watch-dog messages must be answered before failing back to the original primary link (Aboba & Wood, 2003; Calhoun et al., 2003).

A Summary of Diameter's Session Management and Accounting

A *session* is defined as "a related progression of events devoted to a particular activity" (Fajardo & Ohba, 2006). When a Diameter node is required to keep track of sessions for later use the node is considered stateful, otherwise it is stateless. For example, in the case where a server needs to

trigger re-authentication, it needs to maintain the session state. This implies that session management is application specific. For example, a Diameter accounting server maybe configured to keep track of accounting messages such that it is able to eliminate duplicates and fraudulent messages (e.g., a unique Accounting-Start message should not arrive before an Accounting Stop message for an opened session). In cases where the server is stateful, a Diameter client must always send a session-termination-request (STR) to the server so that the server frees its allocated resources for the session.

RFC3588 (Calhoun et al., 2003) and RFC4005 (Calhoun, Zorn, et al., 2005) outline the accounting process. Similar to RADIUS, Diameter accounting requests (ACR) are sent and answers (ACA) are received from servers. A new accounting type, Event record, has been introduced to be used for short connections where accounting Start and Stop records may arrive during very short time periods (e.g., for push-to-talk services). Accounting Event records are also used to indicate accounting problems. For long connections (e.g., VoIP conferencing and file downloads), Start, Interim, and Stop records are used. It is noteworthy to state that in case of reauthorization, an accounting Interim may be sent to summarize the pervious state. In case connection details are modified considerably, an accounting Stop followed by an accounting Start message are sent. The later is case is widely used in practice.

DIAMETER-BASED ARCHITECTURES

As we have seen in the introduction section, there are three network tiers: access, distribution, and core (see Figure 1). In this section, we analyze a selected Diameter application in each tier.

At the Access Layer: 1xEV-DO with a translation agent

Figure 1 shows a simplified 1xEV-DO network where radio network controllers (RNCs) authenticate the mobile call through the RADIUS based A12 interface (3GPP2 A.S0008-B, 2006). The AN-AAA returns the subscriber's International Mobile Subscriber Identity (IMSI) in the Callback-ID AVP to the RNC in the RADIUS access-accept message. Note that since the 1xEV-DO standard does not support Diameter yet, operators may utilize Diameter TAs to convert between RADIUS and Diameter queries. The TA maybe collocated with the AN-AAA as shown in Figure 1. Note that RNCs maybe configured to failover to another AN-AAA for redundancy. Here, the reader should be aware that such failover is RADIUS based and is not based on the Diameter failover mechanisms.

At the Distribution Layer: Diameter MobileIPv4

The PDSN is considered the first IP gateway in 1xEV-DO networks. In MobileIPv4 architectures, MNs are expected to move from one PDSN region into another resulting in MobileIP handovers (HO). The HA represents the home network to which the MN's IP address (Home Address) belongs. Here, we assume that the PDSN/FA and the HA natively support the Diameter MobileIPv4 application (i.e., no translation is involved). When the MN moves into a foreign network, it attaches through a FA that tunnels its traffic back to its home agent enabling it to maintain its IP address while moving (Perkins, 2002; Perkins & Calhoun, 2005).

In 1xEV-DO architectures, the PDSN normally plays the FA role (as well as the NAS role for Diameter) and tunnels the MN's traffic to its HA. The MN establishes a PPP tunnel to the PDSN and broadcasts a registration request (RRQ). Upon receiving the RRQ, the PDSN forwards it towards the AAA for authentication in a Diameter AA-mobile-node-request (AMR) which includes: Session-ID, MN Home Address, Home Agent identity, and MN NAI (Calhoun, Johansson, et al., 2005). Note that such authentication is needed as the RAN may be operated by a different entity from the Internet Service Provider (ISP) who owns the PDSN, HA, and so forth. Thus, upon receiving the Diameter AA-mobile-node-answer (AMA) from the AAA server, the PDSN/FA establishes a MobileIP tunnel with the HA to serve the MN's

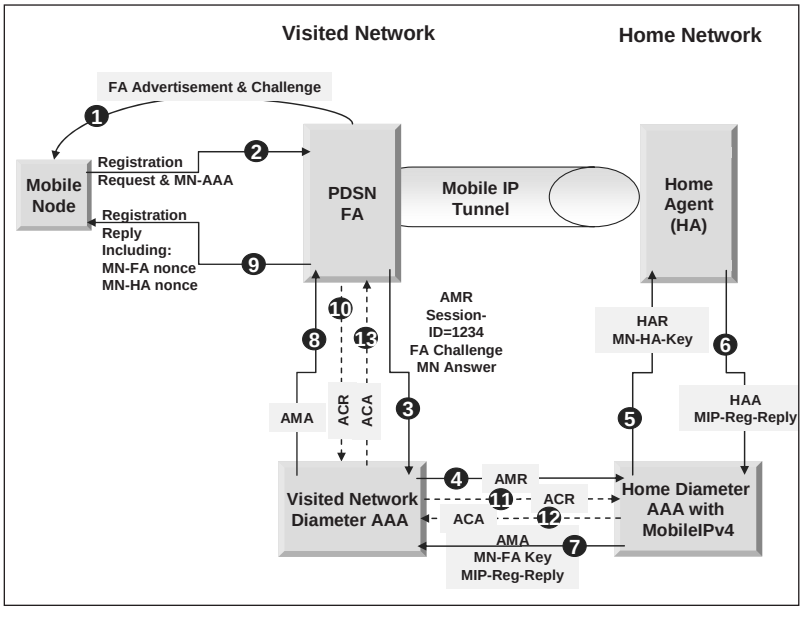
traffic and starts sending accounting requests to the AAA server.

We know when a mobile node roams into a foreign network, the foreign network's AAA usually acts as a proxy and forwards the Diameter requests pertaining to the roaming mobile node to its home AAA (HAAA) server. Foreign mobile nodes are simply recognized by the domains in their NAIs. In these cases, the mobile node needs to establish security associations with HA and/or FA. The HAAA is an attractive element to assist a key distribution mechanism. The Diameter MobileIPv4 application focuses on the role of the AAA as the key distribution element. As shown in Figure 8, the MN-AAA shared secret[8] is used to generate the MN-HA and MN-FA secrets. The FA advertises itself and includes a random challenge and the mobile node replies to the challenge using its MN-AAA shared secret and formulates a registration request (Steps 1, 2). The registration request triggers an AMR at the PDSN to be eventually forwarded to the HAAA (Steps 3, 4). The HAAA validates the request and derives the session keys based on a combination of nonces and the MN-AAA shared secret, then forwards the keys in a home-agent-MIP-request (HAR) to the HA. The HA extracts the MN-HA session key and reformats the nonces generated by the HAAA according to the MobileIP standard and encapsulates them in the home-agent-MIP-answer (HAA) (Steps 5, 6). The HAAA then creates an AMA which includes the MN-FA session key as well as the reformatted nonces from the HAA and forwards it towards the PDSN. The PDSN eventually extracts the session key and sends a registration reply towards the MN (Steps 7-9). The mobile node derives the session keys using the provided nonces and the MN-AAA shared key. Afterwards, the PDSN generates accounting requests (ACRs) reflecting the user's activity (Steps 10-13). The HAAA may be further used to maintain session information such that the same session-ID is used after handovers (Calhoun, Johansson, et al., 2005).

At the Core: IP Multimedia Subsystem (IMS) Interfaces

In the last few years, convergent networking architectures were widely discussed. The IMS was proposed as a radio access agnostic core infrastructure that allows heterogeneous radio networks (e.g., WiMAX, 1xEV-DO, UMTS, WiFi)

Figure 8. AAA role in mobileIPv4 key distribution



to communicate. As such, IMS offers unified services and enables seamless connectivity to the application servers (AS). In this section, we outline the role of Diameter in an IMS-based network. In IMS-based architectures users are granted a private identifier like (nai@operatorA.com) and multiple public identifiers (e.g., john.smith@corporate.com, smith_family@home.com), offering users the capability of sharing business and personal contact information, for instance. The users' profiles are stored in the Home Subscriber Server (HSS). Note that the HSS here plays an authentication and authorization role (AA) and this immediately implies the use of Diameter interfaces.

Let us assume that user 1 roams into provider Y's network and wishes to access a game service located in his/her home network. For that, user 1 first needs to register with the home network through operator Y's infrastructure. As shown in Figure 9, the first point of entry to the IMS network is the so-called Proxy Call Session Control Function (P-CSCF). The P-CSCF is responsible for SIP message processing and may perform various functions in security, compression, and policy enforcement over the SIP messages. The Interrogating CSCF (I-CSCF) is used to facilitate the communication among different operators. Operators have the I-CSCF addresses listed in their DNS servers to allow their I-CSCF to communicate with their peer I-CSCF in the other operator's networks. The I-CSCF normally proxies all SIP messages to the user's Serving CSCF (S-CSCF). The S-CSCF is the element that inspects all user's requests and confirms that they abide by access rights specified for that user. It also acts as a SIP router where it determines whether the SIP message needs to be sent to one or more ASs before granting service (Camarillo & García-Martín, 2004). Note that CSCFs communicate over the SIP-based Mw interface and that only I-CSCFs and S-CSCFs communicate with the HSS over the Cx interface (see Table 1 for the Cx Diameter commands). The Cx interface enables the S-CSCF to download users' profiles from the HSS.

Figure 9. Diameter role in IMS network environments

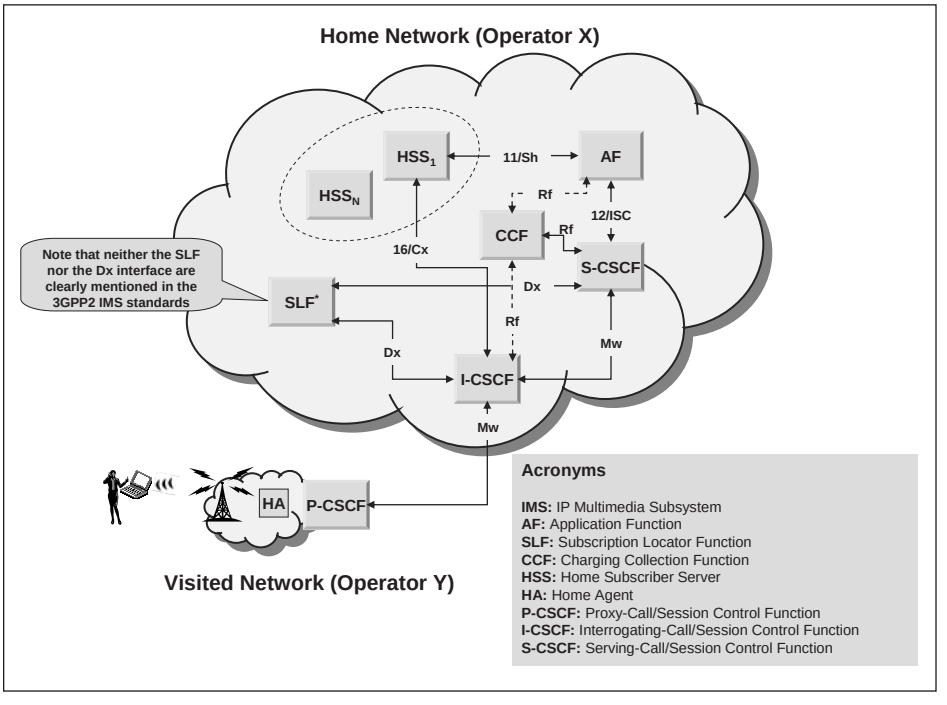


Table 1. The Cx interface commands

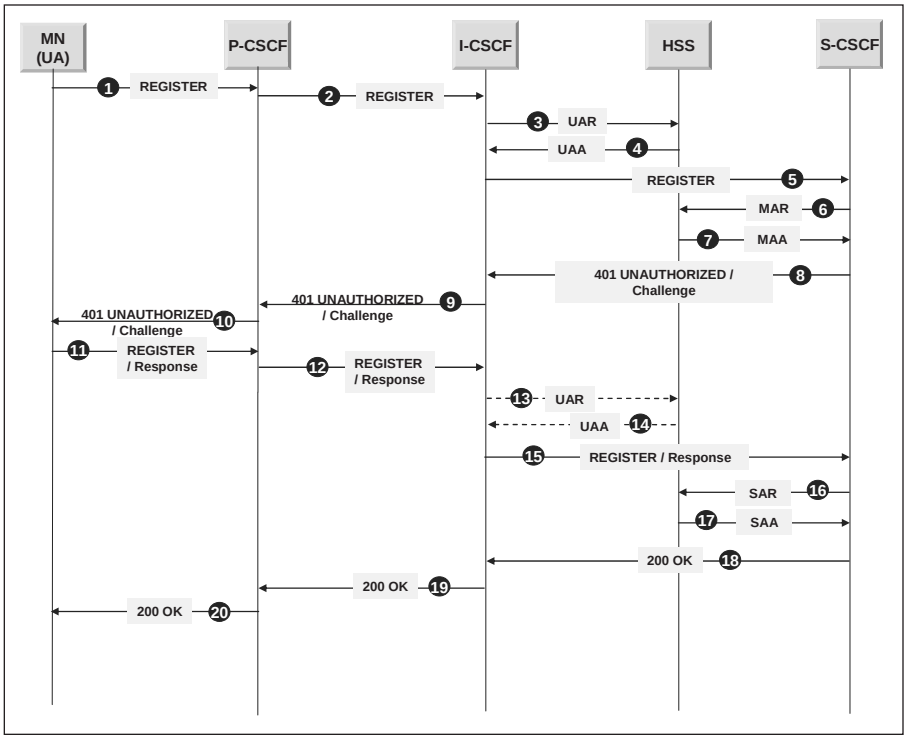
Source	Destination	Command-Name[9]	Abbreviation
I-CSCF	HSS	User-Authorization-Request	UAR
HSS	I-CSCF	User-Authorization-Answer	UAA
S-CSCF	HSS	Server-Assignment-Request	SAR
HSS	S-CSCF	Server-Assignment-Answer	SAA
I-CSCF	HSS	Location-Info-Request	LIR
HSS	I-CSCF	Location-Info-Answer	LIA
S-CSCF	HSS	Multimedia-Authentication-Request	MAR
HSS	S-CSCF	Multimedia-Authentication-Answer	MAA
HSS	S-CSCF	Registration-Termination-Request	RTR
S-CSCF	HSS	Registration-Termination-Answer	RTA
HSS	S-CSCF	Push-Profile-Request	PPR
S-CSCF	HSS	Push-Profile-Answer	PPA

The Dx interface, shown in Figure 9, is essentially the same as the Cx interface. When an I-CSCF wishes to locate the appropriate HSS that holds the user's profile (in order to contact the right S-CSCF for the user's request), it communicates with the subscription location function (SLF). The SLF is simply a Diameter redirect agent, which refers the I-CSCF to the right HSS. Although this interface is not clearly mentioned in (3GPP2 X.S0013-000-A, 2005), it can be simply viewed as a Diameter redirect for a Cx request.

The Sh interface between the HSS and the AS servers facilitates retrieving the application specific user's data, updating it, and receiving notifications when it is changed on the HSS. S-CSCF and AF may generate accounting records and in this case such accounting records are sent over the Diameter-based Rf interface towards the charging collection function (CCF). The CCF may reformat the billing records in the charging data record (CDR) format for further processing in the upstream billing system. It is noteworthy to mention that 3GPP2 X.S0013-000-A (2005) includes a 3GPP2 assigned interface name or number of each interface, for example, 16/Cx, along with the original IMS interface names. However, the use of interface numbering seems to be inconsistent in 3GPP2 standards as in most of the cases original names are only used (e.g., Cx not 16/Cx).

In Figure 10, we utilize a subset of the Cx interface commands to illustrate the IMS registration process for a roaming user. Once IP connectivity is established through the MobileIP procedures, the MN commonly referred to as the user agent (UA) in IMS initiates a registration request towards the P-CSCF. The P-CSCF recognizes that the user belongs to operator X, performs a DNS lookup for Operator X's I-CSCF, and forwards the request to the I-CSCF (Steps 1, 2). When the corresponding I-CSCF receives the registration request, it contacts the HSS over Diameter using the UAR command. Since, the REGISTER request usually carries both the user's public and private identities, the HSS validates that a roaming agreement exists with Operator Y and that the requestor is a valid user and returns a UAA to the I-CSCF (Steps 3, 4). The I-CSCF uses the information in the UAA to locate an S-CSCF and forwards the registration request to it (Step 5). Upon receiving the request, the S-CSCF issues a MAR towards the HSS to obtain appropriate authentication vectors to authenticate the user. The S-CSCF formats the response into a SIP response (401 Unauthorized) that carries a challenge (Steps 6, 7). Once the UA receives the response including a challenge (Step 10), it immediately responds with another registration message carrying a response for the

Figure 10. Initial registration with IMS over the Cx interface



supplied challenge (Step 12). Note that the I-CSCF may perform another UAR to obtain the assigned S-CSCF (Steps 13, 14) either because it is stateless or it is another I-CSCF selected due to DNS load balancing. When S-CSCF receives the second registration request, it validates the user's response (Step 15) and if successful, it issues SAR to HSS requesting its assignment for the user's session and requesting the user's profile. The HSS assigns the S-CSCF for the user's session and sends the user's profile back to it (step 16, 17). At this point (step 18), the S-CSCF issues a SIP 200 OK message to the UA and once received (Step 20), the registration process is complete.

For registered users, when the I-CSCF receives a SIP INVITE request, it queries the HSS for the assigned S-CSCF using the LIR command. If the user's profile is updated, the HSS informs the serving S-CSCF of this change by sending a PPR. The HSS may terminate the user's session by issuing a RTR message towards the S-CSCF (3GPP2 X.S0013-005-A, 2005). As we can see from this short IMS registration walkthrough as well as from the previous sections, Diameter is envisioned to be one of the fundamental protocols used in the future 3G/4G telecommunication infrastructures.

ISSUES AND FUTURE TRENDS

Many standardization and research efforts are underway to upgrade and enhance the current AAA architectures to exploit the security and the scalability benefits of Diameter in the areas of session management, mobility support, distributed online and off-line accounting, and QoS assurance for user services over heterogeneous wireless networks. For instance, Eyermann, Racz, Stiller, Schaefer, and Walter (2006) discuss possible enhancements to maintain consistent accounting reporting in heterogeneous multi-operator environments by introducing a new Diameter accounting application including new commands and AVPs to allow sharing session context information. Moreover,

efforts to attain seamless translation between RADIUS and Diameter are ongoing especially in the areas of matching requirements between RADIUS and Diameter and in the translation of VSAs (Mitton, 2006).

As the future telecommunication networks are expected to be based on IPv6, Diameter implementations over IPv6 were tested and some issues were identified (Lopez, Perez, & Skarmeta, 2005). The tests were conducted based on the Open Diameter[10] implementation. Integrating Diameter with MobileIPv6 is also an active area in both IETF and research. For example 3GPP2 X.P0047-0 (2006) discusses possible enhancements for MobileIPv6 to exploit the security features of the Diameter applications for MobileIPv6 tunnel setup. It also proposes enhancing MobileIPv6 by using Diameter for dynamic selection of home agents.[11]

Finally, continuous efforts are being made to establish a standardized framework for end-to-end QoS for services starting from the calling user at the RAN and ending at the called party whether it is located on the Internet or on another cellular network. 3GPP2 addresses such architectures in the service based bearer control draft document (3GPP2 X.S0013-012-0, 2006). It is noteworthy to mention that Diameter is quickly being considered to support many services. For instance Kim and Afifi (2003) discuss the integration of GSM SIM-based authentication with the AAA over Diameter-EAP application. Moreover, 3GPP2 has adopted Diameter architectures to support simple and multimedia messaging services (SMS and MMS) in (3GPP2 X.S0016-101-0, 2006).

SUMMARY

In this chapter we presented and discussed architecture and protocols for AAA as one of the most important design considerations in 3G/4G telecommunication networks. While many advances have been made to exploit the benefits of the current systems based on the RADIUS protocol, we illustrated its inherent security vulnerabilities. We then surveyed the details of the Diameter protocol and some of its applications. We showed that the Diameter protocol is not only the protocol of choice for the IMS architecture, but it also plays an increasingly important role in the three major network tiers, that is, access, distribution, and core. We demonstrated the role of Diameter in each tier by means of sample call flows in practical 1xEV-DO network architectures. We concluded the chapter with a short summary of the current and future trends related to the Diameter-based AAA systems.

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KEY TERMS

Diameter: Diameter is a new AAA protocol presented in RFC 3588 to replace RADIUS.

IP Multimedia Subsystem (IMS): IP multimedia subsystem is an access agnostic architecture proposed as a core technology for the next generation services.

One Carrier Evolution Data Only (1xEV-DO): 1xEV-DO is a CDMA2000 based cellular access technology proposed to support high rate data services.

Remote Access Dial In User Service (RADIUS): RADIUS is an AAA protocol defined in RFCs 2865 and 2866.

ENDNOTES

1 MMD is defined in all-IP core network standards (TSG X series) found at http://www.3gpp2.org/.

2 Notice that the authentication and the authorization operations are not separated in RADIUS. In other words, to obtain a user's authorization set, user must be successfully authenticated.

3 UDP ports 1812 and 1813 are the standard ports assigned for authentication and accounting respectively.

4 Inter-domain AAA traffic crossing untrusted networks such as in roaming scenarios is usually secured by dedicated VPNs.

5 According to (Aboba, 2005, message 01185) end-to-end security through Diameter CMS (Calhoun, 2002) mentioned in the standard (Calhoun, 2003, RFC 3588) has been abandoned and resolved by the introduction of the Diameter EAP application defined in (Eronen, 2005, RFC4702).

6 If a loop exists, the message is rejected with a DIAMETER_LOOP_DETECTED error message

7 More complex procedures may apply in case of translation.

8 Loosely speaking the user's password

9 These commands are based on the Diameter Cx Application (Application-ID = 16777216), more details can be found in (3GPP2 X.S0013-005-A, 2005; 3GPP2 X.S0013-006-A, 2005).

10 The Open Diameter project, located at [http://www.opendiameter.org/], offers open source C++ implementation of the Diameter base protocol.

11 Dynamic Home Agent (DHA) selection is a method used to dynamically select home agent based on the geographic location of the user such that the network backhaul delay is minimized.

Chapter XIII
Authentication, Authorisation, and Access Control in Mobile Systems

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ABSTRACT

Converging networks and mobility raise new challenges towards the existing authentication, authorisation, and accounting (AAA) systems. Focus of the research is towards integrated solutions for seamless service access of mobile users. Interworking issues between mobile and wireless networks are the basis for detailed research on handover delay, multi-device roaming, mobile networks, security, ease-of-use, and anonymity of the user. This chapter provides an overview over the state of the art in authentication for mobile systems and suggests extending AAA mechanisms to home and community networks, taking into account security and privacy of the users.

INTRODUCTION

Today's pervasive computing environments raise new challenges against mobile services. In future visions, a converged user access network is projected. This means, that one network will be used to deliver different services, for example, broadcast TV, telephony, and Internet. Composed from mobile (e.g., Universal Mobile Telecommunications System [UMTS]), wireless (IEEE 802.11, IEEE 802.16, IEEE 802.20), and wired (cable, Asymmetric Digital Subscriber Line [ADSL]), these networks hide the border between the telecom, broadcast, and computer networks. The common service enables roaming terminals, which can access services independently of the currently used networking technology. Market players in both areas transform into wireless service providers across access networks. Telecom provide packet switched data and mobile services over the fixed network, while Internet service providers run voice over IP (VoIP) and video on demand (VoD) over mobile networks.

The changing environment also changes the management plane of the underlying networks. Providers on converged networks have to change their accounting and billing methods and need to redefine their business models. While commercial

players demonstrate early examples, research in the AAA area focuses on providing a backplane for the upcoming ubiquitous services run over converged networks.

BACKGROUND

The AAA methods employed in current networks were developed for a single type of network, resulting in two different systems, one for telecommunication services and one for computer networks. This chapter addresses AAA in global system for mobil communications (GSM) and UMTS and computer network solutions based on Internet Engineering Task Force (IETF) standards.

The computer networks provide a unified AAA access, and research focuses on extending the existing methods to be suitable for telecommunication services. Extensions for Remote Authentication Dial In User Service (RADIUS) and Diameter are proposed. RADIUS is the current de facto standard for remote user authentication. It uses Universal Datagram Protocol (UDP) as transport. Authentication requests are protected by a shared secret between the server and the client, and the client uses hash values calculated from this secret. The requests are sent in plaintext except for the user password attribute. The Diameter protocol provides an upgrade possibility as compared to RADIUS. While enhancing the security through supervised packet transmission using the transmission control protocol (TCP) and transport layer encryption for reducing man-in-the-middle attacks, it lacks backward compatibility.

Both methods have a different background. The computer networks targeted the person using a computer in a fixed network environment, while mobile systems addressed a personal device in a mobile network. Thus a challenge for telcos is to enhance seamless network authentication towards user authentication for service access. Most companies are also Internet service providers (ISPs), this would be a natural unification of their AAA systems.

A generic approach is taken by extension of the Extensible Authentication Protocol (EAP) family. Development efforts of the Internet and telecommunication world were united on EAP. This protocol family has the potential for becoming the future common platform for user authentication over converged networks. EAP is a universal authentication framework standardised by IETF, which includes the authentication and key agreement (AKA) and Subscriber Identity Module (SIM) methods. EAP-AKA is the standard authentication method of UMTS networks.

Beside the fundamental differences of communication and computer networks, mobility is the key issue for both. Network services should not only be accessible from mobile terminals, but they should be adapted to the quality of service (QoS) requirements of a mobile/wireless link. Improvements of AAA methods are of fundamental importance for mobility, providing fast handover, reliable and secure communications on a user-friendly and privacy protecting basis.

Subscriber Authentication in Current Networks

In GSM networks, the integrated AAA is used for any type of user traffic. The authentication is just one way the user has to authenticate himself/herself towards the network.

To be more precise, the user is authenticated with a PIN code towards the SIM in the mobile phone, then the device authenticates itself towards the network. Device authentication instead of user authentication can hinder the upcoming personalised services because it is hiding the user behind the device. In UMTS, the authentication of the device is two-way. A device can also check the authenticity of the network with the help of keys stored on the SIM.

Integration of the mobile authentication with different external services is not widespread. The telecom providers have some internal services, which can authenticate the subscriber based on the data coming from the network. Credentials could be basically the CallerID, the Temporary International Mobile Subscriber Identity (TIMSI) or other data transformed with a hash function. Access control and authorisation is more an internal

network task. Without considerable extension, the current mobile networks are more islands than connecting networks in the area of AAA. Equipment manufacturers are now recommending various IP multimedia subsystem (IMS) solutions for mobile providers in order to enable integrated and third party service convergence and to enable multimedia content over today's networks.

AAA protocols employed in computer networks are meant to provide services for authenticated users. Current single sign-on (SSO) protocols, like RADIUS, Diameter, or Kerberos provide the identity of the user to third parties. SSOs can use digital certificates, public key infrastructure (PKI) and other strong encryption methods. But, none of them is able to provide such a complete solution like the integrated AAA of the mobile network. Computer network protocols lack the support for fast mobility of moving clients and optimise resource usage for low bandwidth connections.

With incorporating seamless authentication used in network internal services in telecom world and SSO solutions provided by various protocols from computer networks, a unified AAA system will achieve a enhanced user acceptance and service security. In such a system, secure key storage and tamper resistant handling is crucial. Smart cards for key storage and generation will fulfil the security requirements, but usage and distribution of the smart cards is cumbersome. As most users have a mobile phone, the SIM card is a candidate to be a primary smart card used for AAA in a ubiquitous environment (Kálmán & Noll, 2006).

AAA IN CONVERGED NETWORKS

A converged network carries several types of traffic and enables seamless information exchange between different terminals, regardless of transport medium. To enable converged AAA, research work is going on in different areas: enabling wireless LAN (WLAN)-mobile network interworking, enhancing network mobility in wireless computer networks, and reducing resource requirements in cryptography.

Interworking Between Mobile and Wireless Networks

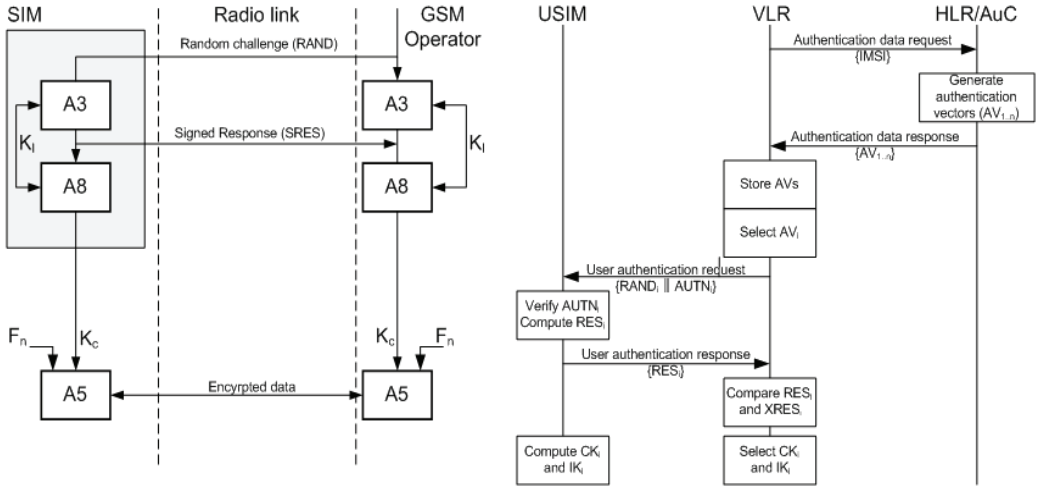
Network convergence is most significant in the wireless environment, having to face varying QoS measures on the radio interface, for example, propagation delay, variation of delay, bit error rate, error free seconds, distortion, signal to noise ratio, duration of interruption, interruption probability, time between interruption, bit rate, and throughput. These parameters will depend on the user and terminal environment and underline that an optimum access will have to use all available wireless and mobile connections. Leu, Lai, Lin, and Shih (2006) have provided the fundamental differences of these networks, summarised in Table 1.

Increased demand for security has improved the security on wireless links, resulting in Wi-Fi protected access (WPA) and WPA2 as draft implementations of the IEEE 802.11i standard. This standard aims at incorporating protocols of

Table 1. Comparison of cellular and WLAN networks

	Cellular	**WLAN**
Coverage	Country-wide	Local
Security	Strong	Depends on setup
Transmission rate	Low	High
Deployment cost	High	Low
License fee	Very high	No need
Construction	Difficult	Easy
Mobility support	High	Poor

Figure 1. Authentication in GSM and UMTS



the EAP family, especially transport layer security (TLS) and SIM.

Most cellular operators are now providing WLAN services using the Universal Access Method (UAM) for authentication. UAM uses a layer 3 authentication method, typically a Web browser to identify the client for access to the WLAN. This raises the problem of mutual authentication, which has been a problem also in GSM networks. By extending to EAP-SIM it would be possible to enable SIM-based authentication in these environments for SIM-enabled devices.

Roaming between access providers is a second issue. Since data between access points are carried over an IP backbone, it is natural to use a network-based protocol such as Radius, suggested by Leu et al. (2006). Transport encryption inside the backbone is indifferent from normal wired practice, hence out of scope for this chapter. In a converged network, where users can switch between mobile networks and WLAN services, a common AAA system has to be operational to ensure correct operation. A unified billing scheme is proposed by Janevski et al. (2006), suggesting to use 802.1x on the WLAN side as shown on Figure 2. The mobile networks WLAN connection is suggested through the RADIUS server used also for access control in 802.1x.

The use of the IEEE 802.1x standard allows seamless authentication, since preshared certificates and key negotiation are provided to the cellular network, where the user is already authenticated. With the use of digital certificates, the system is getting closer to the preferred view of pervasive systems, where the user and the service providers are mutually identified. Since these systems authenticate the user towards several services, privacy is a primary concern. A possible solution, recommended by Ren, Lou, Kim, and Deng (2006) has a secure authentication scheme while preserving user privacy.

In pervasive environments a user connected will experience seamless authentication to all services when connected through a SSO service. Malicious tracking of his/her behaviour or eavesdropping of authentication messages can compromise the user credentials. The SSO service has to be extremely prudent when sending user-related information. Keeping a reasonable level of privacy, the system should deal with questions in location privacy, connection anonymity, and confidentiality (Ren et al., 2006). The recommendations are based on blind signatures and hash chains. Using hash is highly recommended, since a good hash function can provide good foundation for anonymous access and its resource needs are not too high for the current mobile devices, as sometimes blind signatures

based on Rivest-Shamir-Adleman (RSA) scheme may be. In certain environments, the GSM integrated functions may also be used.

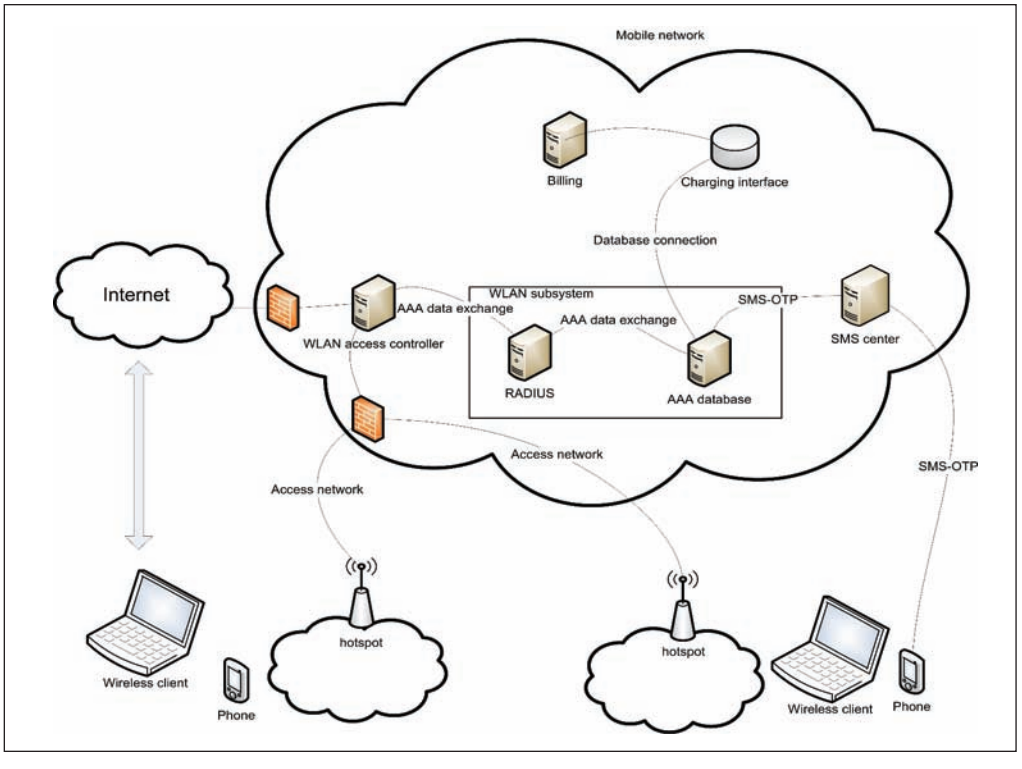
The user retains full control over authentication credentials when composing and generating authentication tokens like the identities suggested by Chowdhury and Noll (2007). Initial service access can be achieved showing one of these tokens after mutual identification between the service and the user. Based on these tokens, no user data can be retrieved nor traced back. If all of the initial identification steps succeed, the exchange of the required credentials can proceed using a freshly negotiated session key.

The base of most authentication techniques is a preshared key, delivered to the user device out-of-band. Authentication can be done for example in mobile phones by inserting a master private key on the SIM at the activation of the card (Kálmán & Noll, 2006).

A different approach is to extend the current mobile network with additional elements to enable network integrated AAA also in an Internet environment. Khara, Mistra, and Saha (2006) suggest including a new node, called Serving GPRS Access Router. This entity acts as a gateway for the WLAN traffic to enter the general packet radio services (GPRS) backbone and enable GPRS signalling to control WLAN. The new protocol set eliminates the need of Signalling System 7 (SS7) in addition to the IP backbone. Khara et al. claim that this solution is superior in terms of speed and overhead compared to the RADIUS-based methods suggested previously. The main drawback is the need of special dual mode devices with a split IP layer, a solution which might not be practical having in mind the basis of 2.5 billion mobile phones available in the market.

For mobile devices limited computational resources and battery power require an effective AAA mechanism. Extension of the GPRS/UMTS network could be potentially more expensive than deploying RADIUS authentication. Handover delay caused by terminal mobility is an issue which might favour GPRS/UMTS protocols.

Figure 2. Integration of radius and mobile network authentication



Authentication in Converged Networks

From the data traffic's point of view, the speed of the network's internal routines does not play a primary role, in VoIP and other sensitive services, QoS is a key parameter. Delay reduction is currently the topic having intensive focus. Interconnecting mobile and IP networks for data traffic is not a challenge, since GPRS has an IP backbone, and UMTS is practically an IP network. Most of the problems begin when the network has to provide a certain QoS in order to support service with time-critical transmission, that is, voice or video calls. Delay in the wired network can be reduced by additional bandwidth to reduce collisions, alternate routing paths, or other methods. But in wireless environments, where terminals move around and connect to different networks, which may be "far" away in terms of network topology, switching the data transfer path is a challenging task.

In the IP world, Mobile IPv6 (MIPv6) was introduced to deal with mobility problems. This protocol works flawlessly for clients that are changing networks with quite low frequency and are connected to a wired network, where additional signalling and other overheads are not causing bandwidth problems. The convergence time of the routing in MIPv6 is quite slow. In a wireless environment every additional message exchange or signalling overhead has a direct influence on usability. When the terminal is moving fast between these distant networks, it may reach a speed, where the routing of MIPv6 can not keep the connection in a correct state. This means that while data traffic could be able to transmit with low average speed, QoS cannot be kept on an adequate level to support VoIP or VoD services, for example. To fight this problem, several micromobility (local area) protocols were developed to support fast moving nodes. Different approaches are used, for example in hierarchical MIPv6 with fast handover adds a *local home agent* into the network. Seamless handoff for MIPv6 tries to lower the handover time with instructing the nodes to change networks based on precalculated patterns.

Handoff between neighbouring IP networks could be done in reasonable time if they are cooperating, but with introducing converged network access, it is likely that the terminal moves between WLAN and UMTS networks and back in less than a minute. Session mobility, for example a VoIP call without interruption, cannot be achieved using current protocols. The key is to reduce the handoff delay in interworking networks. To reduce delay inside the UMTS network, Zhang and Fujise (2006) show a possible improvement for the integrated authentication protocol. One cause of the long delay is getting an authentication vector (AV) if the Serving GPRS Support Node (SGSN) and Home Location Register (HLR) are far away. While roaming, the AV consumption is higher, if the terminal is moving frequently or it is producing significant traffic. The specifications allow a high blocking ratio of 20% for the UTMS network in case of requesting new AVs. The proposal claims to lower this rate to 2%. For each authentication instance, the SGSN consumes one AV from a first in first out (FIFO) storage.

A fundamental question is to allow the size of the AV vector to be customised based on the terminal's behaviour. In the default way, the SGSN executes a distribution of authentication vector (DAV) procedure if all AVs are consumed. Communication between the terminal and the SGSN cannot proceed until the reply is received from the HLR, inserting a potentially high delay into the system. This can lead to call failure, errors in location update, or unacceptable delays in services running on GPRS. The proposed protocol from Zhang and Fujise (2006) implies no change in case of the first authentication to the SGSN, but keeps track of the number of available AVs and sends out a new request when hitting a predefined level. This level can be customised for a network, to reduce or even remove the possible delay of waiting for an AV. The proposal also changes the basic behaviour, asking for new AVs when they are consumed. The original 3rd Generation Partnership Project (3GPP) system asks for them when a new event comes in and no AVs are available.

While reducing delay inside the GPRS network can reduce block probability in reaching network services, also handover functions in IP have to be

revised in order to achieve reasonably fast mobility support. The basic challenge is that currently AAA and MIPv6 are operated independently. This means that the terminal has to negotiate with two different entities in order to get access to the new network.

In MobileIPv6, the terminal is allowed to keep connections to a home agent (HA) and a correspondent node (CN), even when the terminal changes point of attachment to that network. The terminal has two addresses, the home address (HoA) and the care-of address (CoA). The HoA is fixed, but the CoA is generated by the visited network. The mobile IP protocol binds these two addresses together. To ensure an optimal routing in the network, the terminals switch to *route optimalisation* mode after joining a new network. Then it executes a *return routability* procedure and a *binding update* (BU) to communicate to the correspondent node directly. The return routability procedure consists of several messages, which together induce a long delay.

The handover between networks implies even more steps and consumes more time: movement detection, address configuration, home BU, return routability procedure, and a BU to the correspondent node. The terminal cannot communicate with the CN before the end of the procedure.

Fast handover capability is a major research item in IETF for MIPv6, including the standards FMIPv6 and HMIPv6. In addition to these schemes, Ryu and Mun (2006) introduce an optimisation in order to lower the amount of signalling required and thus lower the handover delay between domains. In an IPv6 system, the IP mobility and AAA are handled by different entities. This architecture implies unnecessary delays. Several solutions are proposed to enable the mobile terminal to build a security association between the mobile node and the HA. This enables home BU during the AAA procedure. Route optimisation is a key topic in efficient mobility service provision. MIPv6 optimises the route with the use of the return routability procedure. In wireless environments, the generated signalling messages represent a considerable part of the whole overhead. Moving route optimisation into the AAA procedure can reduce the delay by nearly 50% (Ryu & Mun, 2006). This was enabled by embedding the BU message into the AAA request message and so optimising the route while authenticating. This solution can solve MIPv6's basic problem of supporting different administrative domains and enable scalable large scale deployment.

Lee, Huh, Kim, and Lee (2006) define a novel communication approach to enable communication between the visited AAA servers for a faster and more efficient authentication mechanism. If a terminal visits a remote network, the AAA must be done by the remote system. IETF recommends integrating Diameter-based authentication into the MIPv6 system. But, when the user is using services on the remote network, the remote AAA has to keep a connection with the home AAA. The proposed new approach of Lee, Huh, et al. suggests enabling faster authentication when the terminal moves between subnets inside a domain by exchanging authentication data between visited AAA servers without the need of renegotiation with the HA. Connection to the HA is needed only after the authentication when the terminal executes a BU.

One other aspect is shown by Li, Ye, and Tian (2006) suggesting a topology-aware AAA overlay network. This additional network could help MIPv6 to make more effective decisions and to prepare for handovers and other changes in network configuration. Based on the AAA servers and connections between, a logical AAA backbone can be created, which can serve as administration backbone for the whole network. Signals delivered over this network are topologically aware, so the optimal route can easily be selected and signalling messages can be transmitted over the best route. In exchange to the build cost of this backbone network and some additional bandwidth consumed, MIPv6's security and performance can be enhanced.

As the route of the service access is secured, optimised and delay reduced, one basic problem still remains: how to ensure that the user is the one, the network thinks he/she is. Lee, Park, and Jun (2006) suggest using smart cards to support interdomain roaming. The use of the SIM might be preferable because of its widespread use and cryptographic capabilities (Kálmán & Noll, 2006). The problem of having multiple devices is also

raised here, since a system based on the SIM as smart card will require SIM readers in every device—if a secure key exchange method between the devices is not in place.

Lee, Park, et al. (2006) suggest an entity called *roaming coordinator* ensuring seamless roaming services in the converged network. This additional node provides context management services and enables seamless movement between the third generation (3G) network and WLAN to enforce security in converged networks. In order to provide good user experience in a pervasive environment, additional intelligence needs to be added to the traditional AAA systems to ensure that the terminal selects the most appropriate connection method. This method has to be based on the context and has to be supported in all networks. A smart-card-based secure roaming management framework enables the transfer of the terminals context without renegotiating the whole security protocol set. When the terminal moves into a new network, the roaming coordinator, AAA servers, and proxies take charge of the authentication process. The coordinator, having received a roaming request, evaluates the available networks and chooses the best available one, and then triggers the context transfer between the corresponding AAA servers. When transferring whole user contexts, the system has to consider privacy requirements of the user's identity and his/her profile.

Anonymity and Identity

In pervasive environments, privacy is of key importance. With computers all around, gathering information about traffic, movements, service access, or physical environment, customer privacy must be protected. Køien (in press) suggests a protocol, which is able to provide better protection for the user's privacy than the normal 3G network. Changes in the EAP-AKA protocol are suggested to use only random generated user authentication values. He defines three user contexts implying different key management and authentication schemes, like existing keys for short-term and fresh keys for medium-term access. Identity-based encryption is recommended to enable a flexible binding of the security context to protect the permanent subscriber identity and location data, which will only be discoverable by the home register. The main drawback of the suggested protocol is its higher computing requirements as compared to EAP-AKA, potentially limiting the applicability.

Security and Computing Power

A security protocol in a wireless environment should be fast and secure, and it has to be effective in terms of computing power and low data transfer need. In low power environments an authentication scheme with high security and low computing power is advised. One solution is based on hash functions and smart cards, allowing minimised network traffic and short message rounds used for authentication. Anonymity can be ensured through one-time passwords. While accepting the advantages of a system with smart cards, the use of extra hardware like a card reader is not advisable, due to compatibility issues and power requirements.

Software-based solutions have an advantage, as they only require computing power. Showing the importance of power consumption, a comparison of cryptographic protocols is presented by Lee, Hwang, and Liao (2006) and Potlapally, Ravi, Raghunathan, and Jha (2006) showing, that twice of the transmit energy of one bit is needed to run asymmetric encryption on that piece of information. Symmetric encryption needs, in contrast, around one half of the transmit energy. Most overhead is generated by session initialisation, meaning longer sessions induce lower overhead. There is a trade-off between security and session length. While negotiation overhead is getting lower with long sessions, security risks are getting higher.

This overhead can be lowered by special hardware or software solutions. Hardware needs some power and bigger silicon, while software requires a faster CPU. Hash functions have an energy requirement of around half a percent compared to PKI in generating session keys (Potlapally et al., 2006). Key exchange protocols using elliptic curve Diffie-Hellman (DH) come out much more energy efficient as compared to the same traditional strength DH. The DH calculations demonstrate the trade-off between power consumption and security. In order

to have an efficient operation, the security protocol needs to have the possibility to adapt encryption to the needs of the current application. Authentication token generation can be problematic for devices with limited computing capabilities. Personal area networks (PAN) with multiple devices raise this problem by their very nature.

Security in Personal Area and Home Networks

Efficient authentication and certificate management ensures better usability of PAN devices. By using efficient security protocols, content-adaptive encryption, efficient key and certificate management, considerably longer battery operation is achievable. To enable key management in a PAN a personal certificate authority (CA) entity is suggested (Sur & Rhee, 2006; Sur, Yang, and Rhee, 2006), which will be responsible for generating certificates for all mobile devices within the PAN or home device domain (Popescu, Crispo, Tanenbaum, & Kamperman, 2004). Because of the context of use, the authentication protocol is focused on efficiency by reducing computational overheads for generating and verifying signatures.

Main focus is on reducing PKI operations, which have been proven to be energy consuming. Instead, it proposes to use hash chains to lower communication and computational costs for checking certificates. Former research suggested hash trees in order to authenticate a large number of one-time signatures. By extending these with fractal-based traversal, it has been proven that these trees provide fast signature times with low signature sizes and storage requirements. The personal CA has to be a unique trusted third party in the PAN. It needs to have a screen, a simple input device, and has to always be available for the members of the network. A cell phone with the SIM is a perfect candidate to be a personal CA (Kálmán & Noll, 2006).

In home environments, basically two types of authentication are distinguished: (1) user authentication, and (2) device authentication (Jeong, 2006). Mutual authentication has to be used in order to prevent impersonation attacks (*identity theft*). This requires an SSO infrastructure, which can be for example Kerberos or RADIUS. A special aspect of resource access over the home LAN is that specific privileges are given to selected programs. The AAA server maintains an access control list to ensure correct privilege distribution.

To build the initial trust relationships some kind of user interaction is needed. The key should initially be distributed out-of-band, for example on an USB stick, or by using short range wireless technology, Near Field Communication (NFC), for example (Noll, Lopez Calvet, & Myksvoll, 2006). On home networks, where power consumption is not a problem, PKI may be used for negotiating session keys between devices, since key management in a PKI is simpler than in symmetric encryption and the delay caused by checking certificates and so forth will not be noticeable in this environment. Users authenticated towards the AAA infrastructure can access the resources seamlessly. Initial authentication is done with PKI. In case of mobile devices, also the home AAA can use previously calculated hash values in chain to lower computational cost. These AAA infrastructures can be connected to a providers AAA, for example to use in digital rights management (DRM) or home service access from a remote network (Popescu et al., 2004).

A user moving with his/her devices to the home raises another AAA challenge, the mobile nodes.

Mobile Nodes (Network Mobility)

Movement of whole networks like PANs or networks deployed on a vehicle, introduce a new level of AAA issues. In a conventional network a standard mobility support does not describe route optimisation. Several procedures are suggested to provide this functionality for mobile nodes, like Recursive Binding Update Plus (RBU+), where route optimisation is operated by MIPv6 instead of the network mobility (NEMO) architecture. This means, that every node has to execute its own BU with the corresponding HAs. To solve problems with pinball routing, it uses the binding cache in the CN. When a new BU message arrives, the RBU+ has to execute a recursive search, which

leads to serious delays with a growing cache size. One potential route optimisation is presented by Jeong (2006).

A designated member of the network, called a mobile router is elected to deal with mobility tasks to reduce network overhead. The AAA protocol for this environment defines a handover scheme and tree-based accounting to enable efficient optimisation. They recommend using dual BU (DBU) procedure instead of the existing procedures like RBU+ as a solution for the reverse routing problem raised by mobility. DBU operates with additional information placed into the messages sent in a BU process. This is the CoA of the top level mobile router (TLMR). By monitoring the messages, the CNs in the subnet can keep optimal route towards the TLMR.

Moving subnets are the subject of eavesdropping and possible leakage of the stored secrets. A secure AAA is proposed for network mobility over wireless links, which deals with these problems (Fathi et al., 2006). Secret leakage can be caused by malicious eavesdroppers, viruses, or Trojans. A possibility is to store the keys in tamper resistant modules, like smart cards, the SIM, or trusted hardware modules. Deploying additional modules can be problematic and expensive. Fathi et al. propose a protocol based on a short secret, which can be remembered by humans and used in a secure protocol called Leakage-resilient authenticated key exchange protocol (LR-AKE). This protocol is used for AAA to reduce NEMO latency under 300 ms in order to provide session continuity, for example in VoIP applications, which is important in keeping a good user experience. However, short passwords as proposed with LR-AKE are not advisable. If complex, they will be noted down by the user, and if weak, they are easy to guess.

As network mobility has considerable security issues, it may be not the way to go. Functionality of a mobile network might be achieved by using a dedicated device as a gateway of the PAN. Only this device will show up in the wireless network, and all traffic originating and arriving to the PAN will go through this device and its HA.

After these technical issues of authentication the next chapter will deal with authentication from the user viewpoint.

Customer Ergonomics

There is always a trade-off between user security and ease of use. If the system is prompting for a password for every transaction, it can assume with quite high probability, that the access is enabled just for the correct user. But, that is unacceptable for most of the users in private environments, where convenience is more valued than security. In corporate networks, policies are just enforced and users have to accept it. It would however be problematic if the credentials were only asked once at start-up or connecting to the network, since mobile devices are threatened by theft, loss, and other dangers by their nature of use.

Smart cards could be a solution to have a good trade-off between the usability and security. Since the user will have a token, which he/she has to care of, and exchange keys generated by it, at least it could be secured that the user who is accessing a specified service holds the authentication token. The mobile phone with the integrated smart card, the SIM, is a potential tool for this purpose. As indicated by Leu et al. (2006) the requirement of carrying a SIM reader or equipping all the equipment with SIM cards is neither convenient nor cost effective. The possibility of secure key exchange between user equipment shall be provided.

The cell phone can act as a key negotiator, with its tamper resistant cryptographic functions integrated into the SIM and then exchange the session keys with other terminals with the use of a short range wireless solution. Currently, most of the security problems, besides the user behaviour, are coming from security holes in the software. Having the capability to download new software over the air to the phone ensures the use of recent updates and eliminates this type of security threat (Kálmán & Noll, 2006). Compared to a security token, it may be better to use the phone, since the SIM card can be locked by the provider, so if the device gets lost, the authentication credentials can be withdrawn within short time.

OUTLOOK

Current research is focused on merging basic network functions to enable pervasive computing and network access. The result of these efforts is a converged infrastructure, which is able to handle most of user needs in high quality. The problem of QoS control in wireless systems remains an open one, but experiences of VoIP and VoD services in wireless networks show the adaptability of the user to the current environment.

Mobility of packet data is still to be enhanced, with the challenge of reducing the handover delay. Remote access to home content is just beginning to be spread between early adopters. MIPv6 will address most of the issues sometime in the future, and with the promising extensions, the protocol will be able to handle sessions together with the AAA infrastructure without service interruption. Mobile networks will use WLAN as a high capacity data service, although upcoming solutions and MIPv6 extensions may be able to threaten their use inside dense populated areas, assuming global Wi-Fi roaming mechanisms are in place.

Efforts are being made towards an easy deployable home AAA infrastructure, which can later bear the tasks associated with inner (user management, remote access, user content DRM, purchased media DRM) and outer (authentication towards corporate, provider- or public-based AAA) authentication and access control.

Educating the user might be the biggest challenge, as mobile phone users represent the whole population, and not just the *educated* computer community. The enforcement of the use of smart cards is advisable, where the possible use of the mobile phone shall be investigated.

Now, we can experience the dawn of new social and community services over the Internet. This raises the problem of privacy protection as never before. AAA services must take care of user credentials, and even must ensure that data collected from different AAA providers cannot be merged. So, research in the area of one-way functions, blind signatures, and different PKI methods is recommended.

Finally, current market players also have to change their business plans. Research in the economical area has to point out new objectives to ensure a good working, open, and secure AAA infrastructure which can be used by every service provider while keeping information exchange on the required minimal level.

CONCLUSION

The biggest effort in AAA systems is on extending the capabilities of the existing solutions in telecommunication and in computer networks to an integrated network approach enabling seamless service access of mobile users.

While telecom solutions are usually more secure, user privacy is not a primary concern here. In computer networks AAA solutions are more open and flexible, while the widespread model of "web of trust" methods is not acceptable for commercial service exchange. Ongoing research indicates the potential for a common mobile/Internet authentication suite, potentially based on the EAP.

Interworking issues between mobile and wireless networks are the basis for detailed research on handover delay, multi-device roaming, mobile networks, security, ease-of-use, and anonymity of the user. This chapter provided an overview of the state of the art in authentication for mobile systems.

Extended AAA mechanisms are suggested for home and community networks, taking into account security and privacy of the users. These networks will keep a high amount of personal data, and thus need stronger privacy protection mechanisms. By using link layer encryption, smart cards, and secure key transfer methods the security and privacy protection can be greatly enhanced.

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KEY TERMS

Authentication, Authorisation, and Accounting (AAA): AAA is a system that handles all users of the system to ensure appropriate right management and billing.

Converged Network: Converged network is a network carrying various types of traffic. Such a network is providing services to different terminals, which can access and exchange content regardless of the current networking technology they are using.

Diameter: Diameter is a proposed successor of RADIUS. It uses TCP as a transport method and provides the possibility to secure transmissions with TLS. It is not backward compatible with RADIUS.

Digital Rights Management (DRM): DRM is a software solution that gives the power for the content creator to keep control over use and redistribution of the material. Used mostly in connection with digital media provider companies, but in pervasive environments, users may also require a way to have a fine-grained security infrastructure in order to control access to own content.

Extensible Authentication Protocol (EAP): EAP, a flexible protocol family, which includes TLS, IKE protocols, and also the default authentication method of UMTS, EAP-AKA.

International Mobile Subscriber Identity (IMSI), Temporary-IMSI (TMSI): IMSI and TIMSI is the unique identity number used in UMTS to indentify a subscriber. The temporary one is renewed from time to time, and that is the only one that is used over the air interface.

Public Key Infrastructure (PKI): PKI is a service that acts as a trusted third party, manages public keys, and binds users to a public key.

Remote Authentication Dial in User Service (RADIUS): RADIUS is the de facto remote authentication standard over the Internet. It uses UDP as a transport method and is supported by software and hardware manufacturers. Privacy problems may arise when used on wireless links, since only the user password is protected by an MD5 hash.

Rivest-Shamir-Adleman (RSA): RSA is the de facto standard of public key encryption.

Smart Card: Smart card is a tamper resistant pocket sized card, which contains tamper resistant non-volatile storage and security logic.

Subscriber Identity Module (SIM): SIM is the smart card used in GSM and UMTS (as USIM) networks to identify the subscribers. It has integrated secure storage and cryptographic functions.

Chapter XIV
Trustworthy Networks, Authentication, Privacy, and Security Models

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ABSTRACT

Wireless networks are gaining popularity that comes with the occurrence of several networking technologies raising from personal to wide area, from centralized to distributed, and from infrastructure-based to infrastructure-less. Wireless data link characteristics such as openness of transmission media, makes these networks vulnerable to a novel set of security attacks, despite those that they inherit from wired networks. In order to ensure the protection of mobile nodes that are interconnected using wireless protocols and standards, it is essential to provide a depth study of a set of mechanisms and security models. In this chapter, we present the research studies and proposed solutions related to the authentication, privacy, trust establishment, and management in wireless networks. Moreover, we introduce and discuss the major security models used in a wireless environment.

INTRODUCTION

Wireless networks are gaining popularity. Such popularity comes with the occurrence of several networking technologies raising from personal to wide area, from centralized to distributed, and from infrastructure-based to infrastructure-less. However wireless data link characteristics such as openness of transmission media, make these networks vulnerable to a novel set of security attacks. In order to protect such networks, multiple security solutions were proposed for the authenticating of users, ensuring privacy, and establishing trust. Deploying wireless networks without considering the threats associated to this technology may lead to the compromise of the interconnected resources and also the loss of security.

To ensure the protection of mobile nodes that are interconnected using wireless protocols, several security mechanisms and security models have

been provided. The solutions were made to cope with the features of the wireless environment and the mobile nodes. In this chapter, we present the research work and security solutions related to authentication, privacy, and trust management. Moreover, we introduce and discuss the major security models used in a wireless environment.

The first section of this chapter takes interest to the concept of trust, which can be defined as the firm belief in the competence of an entity to act dependably, securely and reliably within a specified context. Starting from this definition, it is significant that trust implies a level of uncertainty and judgment. This may depend on many factors due to risks associated to wireless networks. In this section, we define the trust in wireless context and discuss its models.

The second section discusses the authentication, which is a crucial mechanism that ensures that a resource is used by the appropriate entities. Actors, architecture, and issues related to authentication in wireless environment are discussed.

The third section discusses authentication models and protocols in wireless LAN (WLAN), cellular, ad hoc, wireless mobile access networks (WMAN) networks. As Mobile IP is becoming a unifying technology for wireless networks, allowing mobile nodes to change their point of attachment without loosing their connections, a particular interest is also given to authentication in Mobile IP.

The fourth section of this chapter discusses privacy regarding location and transaction in wireless environment. The fifth section presents two aspects regarding security modeling in wireless environments. The first is related to the specification of trust, modeling, and verification. The second addresses the specification and verification of security policies that take into consideration wireless threats.

TRUST MANAGEMENT

Trust management represents the skeleton of any network security framework. The absence of a centralized entity, for example, in ad hoc networks makes trust management a challenging problem to address.

Trust Establishment Basis

Trust describes a set of relations among entities engaged in various protocols, which are established based on a body of assurance evidence. A trust is established between two different entities further to the application of an evaluation metric to trust evidence. The established relations may be composed with other trust relations to generate new relations. Trust may influence decisions including access control. To clarify the process of trust establishment, we consider the following example. Assume two trust relations *A* and *B*. Relation *A* states that "*a certification authority CA1 accepts entity X's authentication evidences*" and is established off-line upon delivery of some evidences (e.g., identity, employment card) by X to B. Upon the establishment of A, the certification authority *CA1* issues a certificate binding a public key to X. Then, it stores the relation in its trust database registering X with its certificate. Relation *B* states that "*a certification authority CA2 accepts CA1's authentication of any entity registered by CA1*". To establish *B*, certification authority *CA2* may ask *CA1* to deliver some evidences such as: (1) *CA1*'s authentication of entities is done using satisfactory mechanism and policy; and (2) certification authority *CA1*'s trust database is protected using satisfactory security mechanisms and policies. The establishment of such trust relation leads to the publication of a certificate signed by *CA2*, associating *CA1*'s public key. The relation is then stored in *CA2*'s trust database. The composition of the two trust relations leads to the acceptance of *CA1*'s authentication of *X* by *CA2*.

One of the main properties that need to be handled during trust establishment techniques is transitivity. To decide whether a trust relation is transitive or not, evidences used to establish trust should ensure (1) availability, meaning that evidences can be evaluated at any time by the entities wishing to establish trust; (2) uniformity, meaning that evidences satisfy the same global metrics of adequacy, (3) stability, which means that authen-

tication mechanism cannot change accidentally or intentionally, and (4) log-term existence, meaning that evidences last as long as the time used to gather and evaluate it.

Need for Trust Management in Mobile Networks

While there are extensive research works that contributed to the management of trust in complex systems, the great majority of them was set up for fixed infrastructures; assumed long-term availability and validation of evidences; and generated lengthy validation process. Several characteristics of wireless networks including unreliable transmission range and topology changes made trust management a challenging task. The focus on ad hoc networks was based on the fact that these networks are self-organized and barely suppose the existence of trustworthy nodes. In infrastructure-based wireless networks such as cellular networks and WLAN, the base stations (BSs) (or access points [APs]) are considered trustworthy. Three main requirements need to be fulfilled by trust establishment process in wireless ad hoc networks. First, trust should be established in a distributed manner without a preestablished trust infrastructure. In fact, connectivity to certification authorities' directory servers in the node's home domain cannot be guaranteed in mobile ad hoc network (MANET) when needed. As a consequence, trust establishment in MANET must support peer-to-peer trust relations.

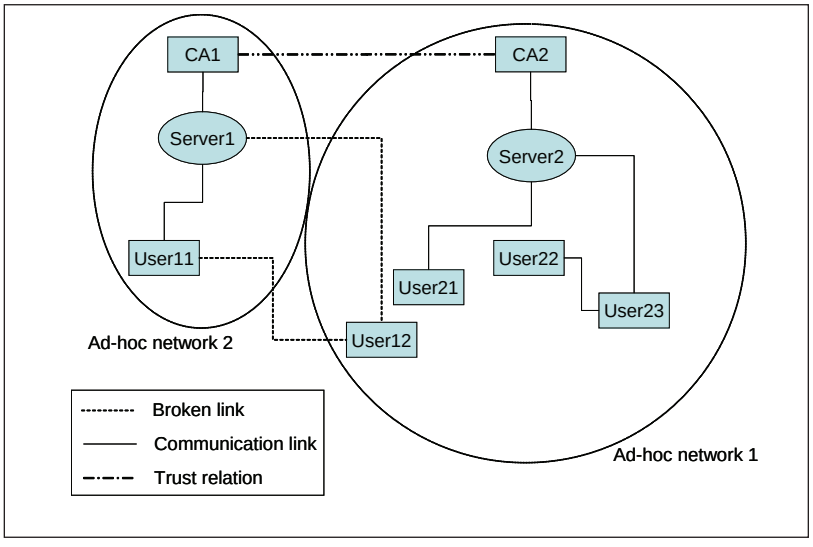
Second, trust establishment should be performed online and trust relations should have short-life period. This is mainly due to the fact that in MANET, when a node moves randomly from a location to another, its security context may change. For instance, when a node moves to a location in which its compromise becomes possible, any trust relation that involves such node should be withdrawn. Such behavior should not affect network connectivity and new trust evidences should be gathered as a consequence. Third, trust establishment should be tolerant to incomplete evidence or unavailable trust relations. In fact, in MANET, it becomes unfair to suppose that all evidences are available to all nodes when they are required to establish trust. Therefore, trust relations should be established using incomplete or uncertain trust evidences, based on the incomplete amount of information that each node holds.

When nodes plan to communicate, they must initially interact with each other and establish a certain level of trust. The change of such level may be triggered further to interaction between neighboring nodes or further to a recommendation from a third party. As a node in the MANET has only a partial view of the whole network, additional mechanisms should be designed to allow these nodes identifying valid trust evidences and prevent intruders from altering them or modifying the trust value of other nodes. To clarify this issue, Figure 1 depicts two networks. In the first network, users *User1x* need to communicate very often with server *Server1*. In the second network, users *User2x* need to communicate very often with server *Server2*. Different trust relations can be established. Nodes in network 1 and 2 trust each other based on identity certificates which are registered by certification authority *CA1* and *CA2*, respectively. In this scenario, User12 has lost communication with server 1 and User11, because it moved out of the coverage. Some among User2x can be found under the communication range of User12. To reach Server1, User12 has to authenticate itself to any User2x and get access to the second ad hoc network. To do so, User12 provides its certificate (as signed by CA1) to User21. User21 has to decide whether to accept such trust evidence. Assume now that the access policy requires that any node that wants to access the ad hoc network should provide a valid identity certificate from a trusted authority. Thus, User21 should contact its trusted certification authority (CA2) and get the CA1 certificate signed by CA2. After that, User21 will be able to valid the certificate of User12. Transitivity of the trust relation is thus established.

Recent Advances in Trust Management

Former trust establishment solutions focused mainly on procedures to locate the communicating peer's certificate in order to determine the cryp-

Figure 1. Trust establishment in ad hoc network



tographic key. In this context, Balfanz, Smetters, Stewart, and Wong (2002) base its solution on using a location-limited channel to allow nodes performing pre-authentication of each other. As the propagation of the channel is limited, intruders have an outside chance to mount a successful passive attack. While pre-authentication does not require a heavy bandwidth, the existence of location-limited channel represents a very restrictive assumption. The approach proposed in Ren et al. (2004) assumes a minimum storage requirement to establish trust in mobile ad hoc networks. A centralized secret dealer is introduced into the network during the system bootstrapping phase and is supposed to be trusted by all nodes. Every node is assumed to have a pair of public/private key where the public key is known by the secret dealer.

In the first part of bootstrapping, every network node receives a pre-computed short list, say SL, from the secret dealer. SL represents k tuples binding node identifiers to related public keys. These bindings are distributed symmetrically, meaning that if node j receives the node identifier of i and its corresponding public key, then node i will also receives node i identifier and its public key. In the second part of the bootstrapping phase, each node generates k certificates, one certificate for every received binding, assuming that every certificate contains the signature on the selected binding from the received secret list. These certificates will therefore be stored locally. The value of k is chosen so that there is a sufficient trust relationship in the network and the distribution scheme should ensure the certainty of being able to establish a trust chain between any two nodes.

After the system bootstrapping phase is finished, there is no need for the secret dealer to continue existing. To accommodate the dynamic changing of the network structure, every node is assumed to be able to establish independent trust relationship with at least two nodes.

When a node leaves the network properly, it broadcasts information about its departure and signs them. Consequently, the receiving nodes revoke the certificate that was issued to that leaving node. One major advantage of this solution lies in the fact that (1) it decreases the length of the trust path, and (2) it is slightly affected by the dynamic nature of the ad hoc network. However, guaranteeing that sufficient trust relationships exist in the network requires a large care during the selection of value of k.

On one hand, the work in Baras and Jiang (2004) proposed to investigate the stability of trust establishment by modeling a MANET as an indirect graph where edges represent pre-trust relations. The two authors cast the problem of trust com-

putation and evaluation by every individual node as a cooperative game and base it on elementary voting methods. In Theodorakopoulos and Baras (2004), the process of trust relation establishment is formulated as a path problem on a weighted directed graph. The vertices in the graph represent the entities and a weighted edge (i, j) represents the opinion that entity i has about entity j. Such opinion consists of two numbers: the trust value and the confidence value. The trust value is an estimate of the trustworthiness of the target, while the confidence value corresponds to the accuracy related to the assignment of the trust value. Using the formal theory of semirings, one can show how two nodes can establish an indirect trust relation without previous direct interaction. For that case, two operators were developed allowing to combine trust opinions along different paths and compute the trust-confidence value between pair of nodes.

GENERAL MODELS FOR AUTHENTICATION IN WIRELESS NETWORKS

In addition to authentication solutions applied to specific wireless technologies, some general models are introduced in wireless networks. This section discusses these models.

Actors in an Authentication System

Basically, an authentication system is composed of three actors: (1) a supplicant, (2) an authenticator, and (3) a trusted third party (TTP). The supplicant is an entity that requests access to network resources. It may be a person, or an application running on a mobile node. The access to protected resources is gained only if the credentials provided by the supplicant are validated by the authenticator. In an authentication system, a credential is an identifier that is used by an authenticator to check whether the supplicant is authorized. It may be symmetric key, a public/private key pair, a generated hash, or some contextual information such as physical characteristic that uniquely identifies a supplicant (e.g., GPS location, signal to noise ratio, etc.). Finally, a TTP is an entity that is mutually trusted by the supplicant and the authenticator and facilitating mutual authentication between the two parties (Aboudagga, Refaei, Eltoweissy, DaSilva, & Quisquater, 2005). An authentication process is made up of a set of messages that are exchanged between these actors (as e illustrated by Figure 2). Authentication includes four components as follows: (1) “S” denotes the supplicant; (2) “D” denotes the destination mobile node; (3) “As” denotes the authenticator; and (4) “Ad” denotes the destination authentication server. Adding a TTP to this model introduces additional exchanged messages in order to establish trust between the different interacting nodes.

Authentication Management Architecture

An authentication system is based on an authentication protocol that fixes the interaction between the different components described previously. The interaction is made using a set of messages between system components. In a wireless environment, node mobility offers many advantages, but at the same time it may affect the overall system efficiency. Consequently, deploying an authentication system in a wireless environment needs to consider several aspects including authenticators’ number and placements. The choice made on the placement of these servers has an effect on the time spent to authenticate a mobile node and the packet loss ratio. Typically, two strategies may be adopted concerning the authentication servers placement. The former aims at placing authentication servers on the same network within mobile nodes. This solution leads to route the two traffics (exchanged data and authentication traffic) within the same network. Consequently, the contention and the packet loss ratio are increased. However, the time spent during authentication is reduced compared with the second solution that aims to place authentication servers outside of the network and thus forwarding authentication traffic outwards. The latter solution reduces the packet loss ratio and liberates the network bandwidth for useful traffic.

Figure 2. Exchanged messages in a hierarchical authentication model

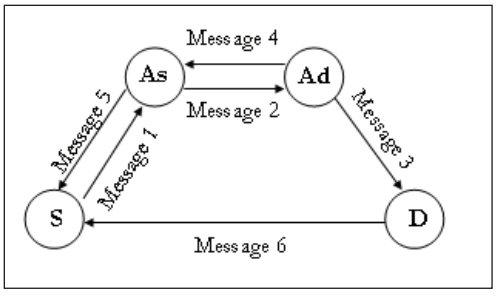
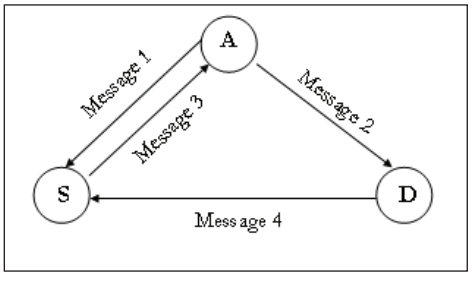


Figure 3. Exchanged messages in a flat authentication model



When deploying an authentication system, a choice should be made concerning how authentication servers manage credentials associated to authorized users. Basically, two architectures may be adopted. The former is an architecture where all authentication servers share the authentication status of all nodes in the network. This model reduces the amount of messages exchanged between interacting nodes, as shown by Figure 3, but holding all authentication information on each authentication server may introduce a processing overload since the verification process is performed on all stored credentials. The second architecture that is deployed is hierarchical where the authentication status of each node is known to a single authentication server. According to this approach, the number of exchanged messages during the authentication process is increased compared with the flat architecture.

Authentication Issues in Wireless Networks

Authentication is among the security services that should be considered in wireless networks. They allow the identification and the validation of credentials provided by users to access services. Deploying authentication in wireless networks needs to consider several issues including:

- **Mobility:** Routes used between communicating nodes change with time and links are unreliable. As a result, exchanged packets may be lost. In ad hoc networks, a set of packets can be exchanged between nodes that belong to the same group. These packets hold information to update a group key. For example, losing these packets is similar to the node that has not received the updated key from the group.
- **Large key size:** Large keys are desirable for their high entropy, but at the same time they would introduce processing overload and also require additional storage space at the mobile node.
- **Reconnection activities:** In wireless networks, connections are often reset and re-established by communicating devices. In this case, every reconnection requires fresh authentication parameters associated to the established sessions. This adds significant overhead.
- **Continuous authentication checks:** To prevent attacker attempts against authentication systems, authentication checks should be continuously performed. These checks introduce additional processing overhead and storage requirement.

In Wei and Wenye (2005), the impact of authentication on the security and quality of service (QoS) was quantitatively illustrated. A possible solution to key length could be sending a cryptographic hash instead of the whole key, but finding a generic cryptographic hash could be difficult for two reasons. First, in a wireless environment, devices are in most cases mobile. The conditions, in which two samples (one sent by the user and the

one held by the server) are taken, vary considerably over time since they are taken under different working conditions. Therefore, two samples of the same object, such as a fingerprint, generated by two different sensors are most likely not identical. Cryptographic hash functions however, do not usually preserve distances and hence two samples of the same object may result in different digests at different conditions.

Introducing sampling in the authentication process may be a solution to reduce bandwidth and power requirements in a wireless environment. As an example of schemes that follow this principle, LAWN is a remote authentication protocol that enables repetitive remote authentication with large keys (Arnab, Rajnish, & Umakishore, 2005). This approach is motivated by the concept of a holographic proof (Polishchuk & Spielman, 1994; Spielman, 1995). A holographic proof is a proof of some fact, so constructed. To verify the proof, one does not need to scan through its entire length (Arnab et al., 2005). The verification process is limited to the examination of small parts randomly selected. According to this technique, a small sample of the authentication token is prepared, which can be used at the remote end to perform authentication with high probability of correctness. This technique allows saving bandwidth and power, since if the length of the original authentication token is *n*, then the selected sample is only $O(\log n)$. As samples may be different, a function that computes the difference between the patterns is needed. This may be achieved by computing the Hamming distance that gives as a result the number of bit positions where two strings differ in.

In the following, several general authentication techniques are detailed.

Password Authentication

Password authentication is among the solutions that are frequently required in wireless networks. Implementations according to this principle are vulnerable to multiple attacks that generally have targeted stored passwords or passwords sent across the network. As a solution to these threats, a proposed scheme should include cryptography techniques to protect stored credentials. Some security protocols are used to secure credentials. As an example of techniques that fulfil these needs, we mention the proposed scheme in I-En, Cheng-Chi, and Min-Shiang (2006) that supports the Diffie-Hellman key agreement protocol over insecure networks and function according to three phases: registration, phase, and authentication.

This scheme employs basic concepts, such as one-way hash function and discrete logarithm problem. During the registration phase, the server assigns smart cards to the users requesting registration. The registration phase is performed only when a new user needs to join the system. However, the login and authentication phases are performed at each user login attempt. During registration, the user chooses an identifier (ID) and a password (PW), it computes $h(PW)$ using a one-way function h. ID and $h(PW)$ are sent to the server through a secure channel. After receiving the registration message, the server calculates $B = g^{h(x\|ID)+h(PW)} \bmod p$, where p is a large prime number initially selected by the server, and g is a primitive number in $GF(p)$. After computing B, the server issues a smart card holding ID, B, p, g and delivers it to the user securely. During login, the user inserts the smart card to a terminal and introduces his/her ID and PW. Then, the terminal generates a login request message based on introduced information then it sends it to the server. At the server side, $B'' = g^{h(x\|ID)R} \bmod p$ is computed, where x is the server's secret key, ID is the user's identity, and R is a random number generated by the server. After that, the server calculates $h(B'')$ and sends it in addition to R to the user. When received at the user side, the user's smart card computes $B' = (Bg^{-h(PW)})^R \bmod p$ and the validity of the server is checked by comparing $h(B')$ and $h(B'')$.

If the server is considered valid, the user's module computes $C = h(T\|B')$, where T is the timestamp associated to the current login, otherwise the server is considered invalid and the user moves again to the login phase. At this step, the user's module sends (ID, C, T) to the server. After receiving the request, the server performs the checks to determine whether the user is allowed

to login. It starts by checking if the format of ID is correct. If that is the case, the server compares T with T'; otherwise, it rejects the login request. T' is the time when the server receives the login request and ΔT is an acceptable time interval with respect to the transmission delay (needed for protection against replaying attack). If $T' - T \geq \Delta T$, the user's request is rejected; otherwise, it computes $C' = h(T \| B'')$ and compares C to C'. If the two values are equal, the login request is considered valid; otherwise it is rejected.

The RADIUS Protocol

The remote authentication dial-in user service (RADIUS) is an authentication protocol that has wide deployment in dial-up Internet services (Rigney, Rubens, Simpson, & Willens, 1997). RADIUS is a stateless transaction-based protocol; it runs over user diagram protocol (UDP). Using this protocol implies that at the end point RADIUS entities must integrate their own reliability mechanisms to handle lost packets. A simple reliability mechanism that is used by the most RADIUS implementations is the retransmission of lost packets.

RADIUS protocol is a client-server model, where authentication messages are exchanged between the RADIUS client and the RADIUS server, through one or more RADIUS proxies. This protocol is used for dial-up services; therefore the client is typically the network access server (NAS) that is in general connected to the remote access server (RAS), which represents the end point of the dial-up connection. The authenticator according to the RADIUS protocol is the RADIUS server that is responsible for receiving user connection requests and authentication. Moreover, RADIUS offers functionalities such as the support for authentication, authorization, and accounting (AAA). The use of plaintext passwords, the hash of passwords, and the keyed hash mechanism based on a shared secret are the basic authentication approaches that are used by RADIUS. These approaches are integrated in the two authentication protocols most used by RADIUS—they are PAP (Lloyd & Simpson, 1992) and challenge-handshake authentication protocol (CHAP) (Simpson, 1996).

However, some vulnerabilities and weaknesses can be found including:

- **Lack of per-packet authentication for access-request packets.** A request authenticator (RA) that is a 128-bit pseudorandom number is included in the access request message. This value is used to hide the user password and does not really provide authentication of access-request messages. As a solution to this problem, it is possible to use RADIUS over IP security (IPsec).
- **Off-line dictionary attacks on the shared secret.** Several implementations of RADIUS allow only the use of shared secrets that are ASCII characters and having lengths that do not exceed 16 characters. Consequently, these secrets have low entropy. Based on this weakness, an attacker may collect access-requests and access-response packets and launch off-line dictionary attacks.

Authentication Between Heterogeneous Wireless Environments

When integrating heterogeneous networks, such as WLAN access networks and mobile cellular networks, many issues should be handled especially for authentication and roaming. For global system for mobile communications (GSM)/general packet radio service (GPRS) networks, the subscriber identity module (SIM) card is used for user identification, authentication, and message encryption. Therefore, it is feasible to authenticate the subscribers in WLAN via exchanging the authentication information between mobile cellular networks and subscribers' SIM cards (Yuh-Ren & Cheng-Ju, 2006). It is assumed that the WLAN access networks and the GSM/GPRS networks can interoperate and exchange system information via the GSM-MAP (Mobile Application Part) interface based on Signaling System 7 (SS7). In this context, a proposed protocol in Yuh-Ren and Cheng-Ju is used to authenticate a GSM/GPRS subscriber in a WLAN access network via the GSM/GPRS SIM card. This goal is achieved by exchanging

some information to verify that the client and the GSM/GPRS have the same secret. The SIM-based authentication mechanism is divided into two phases: Temporary IP Address Acquisition Phase and Subscriber Identity Verification Phase. In Temporary IP Address Acquisition Phase, the mobile station (MS) attaches to the WLAN access network and discovers the DHCP Server to acquire the IP network configuration parameters. Subsequently, in the Subscriber Identity Verification Phase, the MS exchanges the authentication information with the WLAN Authentication Server to manifest the subscriber's identity (Yuh-Ren & Cheng-Ju). For Universal Mobile Telecommunications System (UMTS), the UMTS subscriber identity module is used for authentication.

AUTHENTICATION APPROACHES FOR CELLULAR AND MESH NETWORKS

In this section, we introduce authentication solutions for cellular and mesh networks.

Key Management in Wireless Sensor Networks

The wireless sensor network (WSN) represents a promising technology whose key idea lies in the scattering of tiny devices which are endowed with sensing, processing power, and wireless communication capability. These devices are intended to be deployed in a specific geographic area to sense change of some parameters (e.g., temperature, object movement, and noise) for several purposes including target tracking, environmental monitoring, and surveillance.

A large set of security issues and challenges in WSN networks are described in Pathan, Lee, and Hong (2006) and Karlof and Wanger (2003). Due to the known resources constraints in sensor nodes, it is not feasible to use the traditional pair-wise key establishment techniques such as public key cryptography, which are too computationally intensive to ensure authentication and privacy. On the other hand, symmetric cryptography in WSN is not appropriate since the key may be easily eavesdropped during distribution. To address the issues, recently, several key distribution schemes were proposed which are based on pre-distributed keys or keying materials for key generation. The issue comes down to finding an efficient way for distributing key segments and materials before deployment of nodes.

In sensor networks, key distribution solutions can be classified into random, deterministic, and hybrid ones. For additional information, the reader is refereed to Camtepe and Yener (2004) where a survey on key distribution in sensor networks is provided. For peer-to-peer wireless sensor networks, where no infrastructure exists and nodes are randomly deployed, Eschenauer and Gligor (2002) proposed a random approach that is based on probabilistic key sharing among sensors and relies on a shared key discovery protocol for distribution and revocation of keys. The key distribution scheme has three phases: (1) the key pre-distribution, (2) shared-key discovery, and (3) path-key establishment. The key pre-distribution is preformed off-line before sensor nodes deployment. It consists of distributing a set of keys (key ring) from a large key pool. Shared-key discovery takes place during the initialization of the network. Each node broadcasts the list of identifiers of keys on their key ring. Consequently, every node in the network will discover the list of neighbors with which it shares a key. A routing link will exist between two nodes only if they share a key. As nodes give trust to each other, the same key can be shared by more than a pair of nodes. During the last phase, a path-key is assigned between a pair of sensor nodes that do not share the same key by relying on the set of intermediate secured links established at the second phase.

Du, Deng, Han, Chen, and Varshney (2003) exploit the knowledge of the node deployment to pre-distribute keys. A pair-wise key is distributed between each pair of neighboring nodes by exploiting the knowledge about the nodes that are likely to be neighbors of a sensor node. However, as the number of neighbors can be huge, a sensor may not be able to store all the related secret keys. To alleviate the problem, the use the random key

pre-distribution scheme proposed in Eschenauer and Gligor (2002) reduced the amount of memory required.

In hierarchical wireless sensor networks, a hierarchy among nodes exists. BSs play the role of cluster supervisor and are more powerful that other sensor nodes in terms of transmission range and processing and storage capability. These BSs are considered as tamper resistant nodes. In this case of sensor networks, the key distribution becomes easier where BSs will handle the distribution of keys. A BS may share distinct pairwise keys with each sensor in the cluster that it handles. These keys can be used to establish other secure links between two sensor nodes where a BS will intermediate the establishment of a pairwise key between two different nodes.

Authentication Models for WLANs

Several models have been proposed for authentication in WLANs. These models are classified into categories according the techniques used to authenticate mobile nodes.

Web-Based Authentication Model

The Web-based approach for authentication is adopted due to the simplicity of the approach and the possible use of this technique without the need, at the user side, of special software or hardware. The simplicity of this technique is based on the use of secure socket layer (SSL). A Web server intercepts the user's HTTP traffic and redirects the user to the authenticator Web interface. The user provides his/her identity and password. The transmission of these credentials is protected by the SSL session, which encrypts the traffic between the mobile node browser's and the Web server. This method is simple to implement but does not result in a negotiated encryption key at the WLAN frame layer that is used by algorithms such as temporal key integrity protocol (TKIP). Consequently, after the accomplishment of the login phase, traffic at the MAC layer may remain unencrypted.

802.1X Authentication Framework

This framework is adopted for WLAN authentication and integrated with various key agreement protocols between the supplicant and the 802.11 AP for deriving the layer-2 cryptographic keys.

There are many authentication protocols in 802.1X that are certificate-based and can be used for devices as well as users. A digital certificate issued to a device and integrated physically into that device provides a strong mean to identify the device during the authentication process. A device may be of two kinds: (1) a user device (e.g., laptop, PDA, etc.), or (2) network equipment such as APs, routers, and so forth. A unique identity of the device may be deduced from the combination of the media access control (MAC) address, the product serial number, and others parameters, by using a hash function, for example. This unique identity may be used as the subject identity in the device certificate. A mutual authentication is needed in this case to ensure strong authentication. During this phase, the device uses its private key in to perform some verification tasks such as signing a nonce.

The Point-to-Point VPN Model

The use of IPsec virtual private networks (VPNs) provides an interesting mean to ensure confidentiality for data across the air interface. Thus, it is possible to use it to perform authentication for mobile nodes. In this model, the supplicant software establishes an IPsec VPN with a VPN server, which may be the AP or another device behind the AP. All data traffic generated by the client is tunnelled through the established VPN. According to this scheme, failure in the authentication process means that the IPsec VPN fails to be established and the supplicant's IP address is de-allocated. In this case, a threshold associated to the number of allowable failures by the supplicant may be fixed.

Authentication Protocols for GSM

Authentication protocols are considered among the main components of the GSM architecture. Several protocols proposed in this context have presented

several drawbacks such as bandwidth consumption between the Visitor Location Register (VLR) and the Home Location Register (HLR), storage overhead in VLR and other insufficiencies such as bandwidth consumption if the MS moves frequently and requests several VLRs in a short period. The Authentication Center (AuC) is in charge of performing authentication in the GSM. It keeps the secret key K_i shared with the subscriber and generates the set of security parameters for requests associated to the authentication protocol of HLR. Subscriber's secret key is hold in the SIM card of the MS. When the subscriber registers for the first time, it gets a unique identity and an International mobile subscriber identity (IMSI) from the AuC. Among the solutions to improve such protocols, the authentication protocol proposed in Chang, Lee, and Chang (2005) provides mutual authentication between VLR and the MS. According to this protocol, the HLR makes the visiting VLR and MS share a temporary secret key K_T, which is computed by HLR using the algorithm A3and having as input both K_i (the secret key shared between MS and HLR) and R (a random number generated by HLR).

Moreover, HLR computes the certificate $CERT\_VLR = A3(T, K_i)$ for the visiting VLR of MS, where T is the timestamp sent by MS. This certificate is used to authenticate the validity of VLR. According to this authentication process, an authentication request including the temporary mobile subscriber identity (TMSI), the location area identity (LAI) and T is sent to VLR when the MS enters a new visiting area and asks for new communication services. After receiving the request, the new VLR uses the received TMSI to get the IMSI from the old VLR that will be sent with its identification D_v and T to the HLR through a secure channel. The HLR checks the validity of the D_v and T. If they are valid, it computes $CERT\_VLR = A3(T, K_i)$ and $K_T = A3(R, K_i)$ then it transmits the computed results and R to the visiting VLR. Otherwise, the HLR will terminate the authentication process. Receiving this information, the VLR computes $SRES = A5(R_1, K_T)$ and stores it in its database, where R_1 is a random number generated by the same component for the current communication. After that, the set of parameters composed of R, R_1, T and $CERT\_VLR$ is passed to the MS. Then the MS checks first the validity of T. If it is valid, it computes $CERT\_VLR'$ and compares it with the received $CERT\_VLR$. The authentication process will be halted if the two values are not equivalent; otherwise, MS computes $K_T = A3(R, K_i)$ and $SRES' = A5(R_1, K_T)$. Then, the computed $SRES'$ is sent back by MS to VLR. The latter compares it with the $SRES$ stored in its database to decide whether the request is considered valid; otherwise, it is rejected.

As long as the MS stays in the service area of the same visiting VLR, the latter does not need to request HLR for another authentication parameters but it generates only the random number, called R_j, at each *jth* communication (where $j > 1$ and $j \in 1$). This random number is used to compute $SRES_j = A5(R_j, K_T)$ that will be stored in the VLR database then R_j will be sent to the MS. The latter will compute and send $SRES'_j = A5(R_j, K_T)$ to VLR that checks whether the two values are equal or not. In the case of repetitive communications that are performed by the MS at the same area of the visiting VLR, mutual authentication is not ensured since only MS is authenticated, not the VLR.

To overcome this drawback, an improvement providing mutual authentication to the previous authentication scheme, is proposed in Chang et al. (2005). According to this scheme and while MS asks for the *jth* communication, VLR uses both K_T and T_j as inputs for the A3 algorithm to generate the certificate $CERT\_VLR_j$, where T_j is the timestamp generated by MS and included in the authentication request. This certificate is the means that will be used by the MS to authenticate the VLR. This check will be performed by the MS when it receives the $CERT\_VLR_j$ and proceeds to the computation of $CERT\_VLR'_j = A3(T_j, K_T)$. If the two certificates are equivalent then the VLR is authenticated successfully.

To enhance authentication in addition to ensuring mutual authentication, some modifications were proposed in Chang et al. (2005) including basically two phases: (1) the first authentication in the visiting VLR; and (2) the *jth* authentication between the same visiting VLR and the MS. The

main idea of the first phase is to use $(R \| T_1)$ instead of R_1 to compute. The second phase handles repetitive communication between the visiting VLR and MS, the signed result $SRES_j$ is computed by using $T_{j-1} \| T_j$ and K_T as the inputs of A5 algorithm, where T_{j-1} is the timestamp associated to the $(j-1)th$ authentication and T_j is the timestamp generated by the MS for the *jth* authentication. Moreover, the certificate $CERT\_VLR_j$ of VLR is computed by using K_T and T_j using A3.

Kerberos Based Authentication Schemes for Ad Hoc Networks

Several authentication solutions that have been proposed at first for wired networks may be used in wireless environment by introducing some enhancements. Among these schemes, we mention Kerberos that has been implemented and tested in multiple production environments. In this context, a Kerberos assisted authentication in MANETs, known as *Kaman*, is proposed in Mcdonald and Pirzada (2004). This scheme adapts the Kerberos standard version to the wireless environment constraints. According to this scheme, secret keys or passwords are only known by users whereas the servers know a cryptographic hash of these passwords. Moreover, All Kaman servers share a secret key. These servers periodically, or on-demand, replicate their databases with each other in order to avoid a single-point-of-failure issue. Kaman uses a modified version of the Kerberos 5 protocol for authentication in ad hoc networks that eliminates the use of a ticket granting server (TGS). The adopted authentication protocol is described in Mcdonald and Pirzada . In addition to the basic authentication steps, the proposed protocol details key revocation operations, server elections and the replication of repository strategy.

Authentication in Mobile Ad Hoc Networks (MANETs)

According to the various constraints that characterize a mobile ad hoc network, an authentication mechanism should present low computational complexity and low bandwidth consumption. In Tsai and Wang (2007), two authentication mechanisms have been proposed to ensure cluster and individual authentication. The first authentication mechanism aims to verify whether the mobile node belongs to the same group or whether the message came from a node in this group. During the authentication process, the originator sends the original message and the cluster signature. The cluster signature is generated using the timestamp and the original message. At the destination node, the cluster signature is verified to determine if the received packet is valid or belongs to an attack traffic. The output packet, PKT_M, sent by the source is the following:

$$PKT_M = \{MAC_T, T_{stamp}, E_{Ks}(MAC_M, T_{stamp}, M)\},$$

where $MAC_T = H(K_C, T_{stamp})$ is generated using the timestamp and the common secret key, K_C that is used if there is not an available session key, denoted K_S. This key will be generated only if the individual authentication is performed successfully and is used to calculate MAC_M using the expression: $MAC_M = H(K_S, T_{stamp}, M)$. If the output packet is received by an intermediate node, the latter performs the following checks:

1. It computes $MAC_T = H(K_C, T_{stamp})$
2. It checks if T_{stamp} is within a reasonable time delay range.

If these two conditions are satisfied, the intermediate node forwards the packet to the next node; else it will be discarded. If the next node is the destination, it performs the two tasks in a similar way to an intermediate node, then it decrypts $E_{Ks}(MAC_M, T_{stamp}, M)$ and checks MAC_M by computing $H(K_S, T_{stamp}, M)$. After that, it verifies if the decrypted T_{stamp} is the same as the one that is added to the packet without encryption. If all these checks are performed successfully and all conditions are satisfied, the packet is considered valid; otherwise, it is discarded.

The second authentication process, called individual authentication for unicast, allows the verification of the identity of a user or a node in a

group or the verification of the message originator. Since public-key cryptosystems are unsuitable for mobile ad hoc networks due to their high computational complexity, a low-power-consumption authentication procedure, based on secret sharing, is proposed. As mentioned in cluster authentication, individual authentication is required before generating the session key, which is shared between the source and the destination contrary to the common key that is shared between all the group nodes. The individual authentication mechanism is performed as follows: the source node S initiates a route discovery process to deduce a routing path from S to the destination node D. Next, S generates a random number, called a_0 and a random challenge number $RAND_S$.

S uses the function $f_1(x) = a_1 x + a_0 (\text{mod } p - 1)$. Based on this function, it generates a secret shadow associated with S and D, using an identity number of D (ID_S) that has the following expression: $K_{S,W} = f_1(D_S)$. The parameter a_1 is computed by S by satisfying the following expression:

$$K_{S,W} = f_1(ID_S) \bmod (p-1) = (a_1 \cdot ID_S + a_0) \bmod (p-1).$$

After that, S generates the session key $g^{a_0} \bmod p$ that is recovered at D. Γ is computed by S using $f_1(x = 1)$ as follows: $\Gamma = g^{f_1(1)} \bmod p$. Since these operations are performed, S sends the authentication packet that includes Γ and $RAND_S$ to D through the routing path deduced at the starting of the authentication process. At destination node, Z_D is computed that is the inverse of $(D_D - 1)$ on modulo $p - 1$ which satisfies the following relation: $(D_D - 1) \times Z_i \equiv 1 (\text{mod } p - 1)$. D uses the received Γ and a set of secret parameters called, $\Lambda_{D,S}$ ($\Lambda_{D,S} = (g^{K_{D,S}}) \bmod p$) to compute K_S according to the following expression:

$$K_S = (\Gamma^{ID_D x Z_D} \big/ \Lambda_{D,S}) \bmod p.$$

Using this key, the destination encrypts the received challenge, $RAND_S$, and obtains the authentication reply code $AUTHR_S$ defined by $E_{K_S}(RAND_S)$. The generated $AUTHR_S$ and a regenerated $RAND_D$ are included into a confirmation packet that is forwarded to S via the routing path. Upon the reception of this packet by S, it computes the session key V as follows: $V = g^{a_0} \bmod p$. Then, it compares the received $AUTHR_S$ with $E_V(RAND_S)$. If the two parameters are equal, a common session key is obtained $K_S = V = g^{a_0} \bmod p$. After performing all these steps, S transmits the data packets via the secure routing path to D. The first packet should contain $AUTHR_D$ that is needed by D to verify the identity of S.

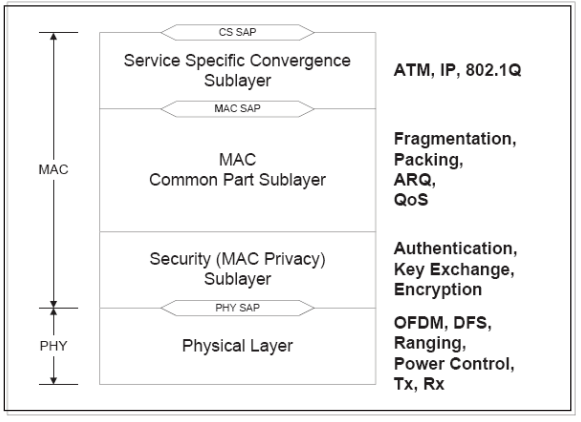
Authentication in 802.16 WMANs

As described by Figure 4, the 802.16 protocol layer consists of the physical layer and the MAC layer that is divided into three sublayers that are: (1) the security sublayer (or MAC privacy sublayer), (2) the MAC common-part sublayer, and (3) the MAC convergence sublayer. The MAC security sublayer supports security mechanisms such as authentication, key exchange, and also encryption. An 802.16 network or cell consists of one (or more) BSs and multiple subscriber stations (SSs). In addition to these components, it may be also additional entities within the network, such as repeater stations (RSs) and routers, ensuring connectivity of the network to core or backbone networks. An SS must perform a number of tasks that include authentication before gaining access to the network. During this phase, the SS must be authenticated by the BS, using the privacy key management (PKM) protocol that is detailed in Hardjono and Dondeti (2006). In such networks, each SS has an X.509 digital certificate (Housley, Polk, Ford, & Solo, 2002), which is integrated into the device hardware at manufacturing. The private key that is assigned to the certificate is embedded in the hardware in a way that is unfeasible for an intruder to read or modify it.

According to the IEEE 802.16 standard, only the SS is assigned a certificate and not the BS. Consequently, the mutual authentication is not ensured since the BS does not authenticate itself to the SS.

The PKM protocol first establishes a secret symmetric shared key between the SS and the BS that is called authorization key (AK).This key is used to ensure the exchange of the traffic encryp-

Figure 4. The 802.16 protocol layers



tion keys (TEK), in a secure manner. According to the PKM protocol, the authentication is performed through the exchange of three messages: (1) the authentication information; (2) the authentication request; and (3) the authorization reply sent by the BS to the SS. The first message sent by the SS during the authentication process contains the following information related to the SS: the MAC address, Rivest, Shamir, & Adleman (RSA) public key, X.509 certificate, list of the cryptographic capabilities, identifier of the primary SA (SAID), and the X.509 CA certificate of the manufacturer of the SS device. This message is facultative and allows the BS to verify if the SS has a valid primary SA and both certificates (for SS and manufacturer) are valid.

The second message sent by the SS to the BS in order to request an AK and the set of SAIDs of any static SA where the SS is authorized to participate. This message contains the same parameters as the first message (without the CA certificate of the manufacturer), only the added parameter is the SS device serial number and the manufacturer ID. The third message is sent by the BS to the SS after verifying its certificate and checking the set of cryptographic capabilities associated to it. The authorization reply message contains: A unique AK, encrypted with the RSA public key of the SS; a 4-bit key sequence number, used to identify different generated AKs; a key lifetime value associated to the AK and the SAIDs and properties of the primary SA and the set of static SAs, if there exist, for which the SS is authorized to obtain keying information.

Authentication in Mobile IPv6

In a Mobile IPv6, a mobile node (MN) exchanges with the home agent (HA) a set of messages that include signalling messages, binding update (BU) and binding acknowledgment (BA) (Johnson, Perkins, & Arkko, 2004). During the registration process, BU and BA messages are used. Moreover, BU messages may be used by an MN to inform other IPv6 nodes about its current care-of address that is registered at the home agent. To secure MIPv6 signaling messages between MNs and HAs, especially for BU messages, an alternate solution to IPsec, has been proposed in Patel, Leung, Khalil, Akhtar, and Chowdhury (2006). This method is a lightweight mechanism to authenticate the MN at the HA. According to this mechanism, authentication is ensured using a MIPv6-specific mobility message authentication option that can be added to MIPv6 signaling messages. Moreover, authentication is based on a shared-key-based mobility security association between the MN and the respective authenticating entity. As defined in Patel et al. (2006), the *shared-key-based mobility security association* is a security relation between the MN and its HA, used to authenticate the MN. The shared-key-based mobility security association consists of a mobility Security Parameter Index (SPI), a shared key, an authentication algorithm, and the replay protection mechanism in use.

MN must use the Mobile Node Identifier option, specifically the MN-NAI mobility option as defined in Patel, Leung, Khalil, Akhtar, and Chowdhury (2005) to identify itself while authenticating with the HA. This option is used to authenticate BU and BA messages. When a BU and BA is received without this option field and the entity receiving it is configured to use it, the received messages will be discarded by the HA. The structure of the mobility message authentication option is detailed in Patel et al. (2006).

PRIVACY PROTECTION

In this section, we detail basically a set of techniques that allow location privacy, and also ensure transaction based privacy.

Location Privacy

When designing wireless communication systems, location privacy should be considered to protect mobile nodes against a set of attacks. Location may be determined by an attacker by decoding packet contents and addresses or even by correlating different transmissions using a model of the user's movement. Using localization information, an attacker is able to track users especially where anonymous users are communicating. In this way, solutions ensuring location privacy are needed in addition to the set of techniques used to ensure confidentiality of transmitted data over the wireless network. The aim of these techniques is to render the intruder unable to correlate two locations.

For ad hoc networks, the privacy problem appears when adopting geographic routing that utilizes only location information to perform packet forwarding. While geographic routing improves routing performance, it introduces a problem related to location privacy. The information may be used by an intruder to reveal the target location. To preserve location privacy, an anonymous geographic routing algorithm that is based on the principle of dissociating user's location information with its identity, is proposed in Zhou and Yow (2005).

For wireless personal area networks, the location privacy problem is faced with some available standards. For example, packets exchanged between Bluetooth devices always contain the Bluetooth hardware address of the sender and the destination or an identifier which is directly mapped to this address. Consequently, an intruder is able to collect the Bluetooth hardware addresses of these devices. The eavesdropping of such kinds of information may be done remotely, by a device having a stronger antenna. Then the intruder can keep track of the place and time mobile devices. In Singelee and Preneel (2006), techniques that aim to solve the location privacy problem have been proposed. Since Bluetooth operates on the media access control layer, proposed solutions are integrated at this level, focusing the following four possible scenarios: (1) the mobile devices share a symmetric key, (2) the mobile devices know each others' addresses, (3) a secure extra communication channel is used, and (4) nothing shared between mobile devices.

The technique proposed for the last scenario is interesting since the two communicating mobile nodes have nothing shared and do not know each other's addresses. In this case, the mobile device that offers service (identified as A) generates a random identifier RA and broadcasts it during the initialization phase. When a mobile device (identified as B) needs to use these services, it generates a random identifier RB then puts the RA in the address field of the destination and its identifier in the source address field. According to this technique, the device does not know with whom it is exchanging messages. The reuse of RA and RB allows an attacker to link all messages in one communication round. Another technique may be adopted when the two mobile devices do not share information and that ensures location privacy, is to broadcast any message without specifying identifiers for communicating nodes.

Transaction Based Privacy

One goal of privacy is to ensure the concept of unlinkable unit of communications. According to this concept, an attacker is tolerated to link any communications within one unit but it is prevented from making the link between two different units. This unlinkability may be provided on a transaction granularity, as proposed in Yih-Chun and Helen (2005). A transaction may be defined as a stream of packets sent from the source to the destination, and another stream of packets sent as response by the destination. Session-based services such as SSH or Telnet may be considered as a sequence of transactions. Linkability between transactions may be decreased with time; after a sufficiently long time, the correlation between two transactions is unfeasible. Based on this principle, the introduc-

tion of random silent period for each node may be a solution to ensure privacy. During this period, the node does not forward or transmits any packets. This technique is not supported by all kind of applications. Voice over IP is among applications where latency is not tolerated.

In addition, information about the occurrence of a transaction should be protected to prevent attacks that are executed at the completion of a given transaction. For example, an intruder may need to determine the occurrence time of a transaction in order to capture the transaction output that may hold a set of information that helps compromising the system or collecting information about it. Ensuring time privacy may be achieved using several techniques that are mostly integrated in transaction-based systems. A random behavior may be another solution that prevents intruder from learning the transaction occurrence time. For example, it is possible that the execution of a transaction delivers only a partial output and the remaining results are provided when needed by requesting them or by informing the service provider node about this need. This technique ensures time privacy since the completion time associated to the execution of a transaction is based in some cases on the reception of the complete output that may be variable in time. Another technique that may be adopted is a dynamic scheme that order transactions following a priority order that takes into consideration multiple parameters such as outputs needed for next transactions, available resources (storage, processing) for processing nodes, and so forth.

SECURITY MODELS

This section takes interest into three aspects in modeling security. The first aspect is related to theories of trust representation, modeling, and verification. The second aspect is related to security policy specification and verification.

Trust Representation, Modeling, and Verification

Trust management systems represent a generalization of the traditional security mechanisms such as authentication and privacy by adding heterogeneity and distribution. Several trust management systems were proposed including Policymaker, Keynote trust management system, and Relational-based formalism of trust.

A number of trust management systems were developed including X.509 (Arsenault & Turner, 2002) model, SPKI (Ellison et al., 1999) and PGP trust model. The X509 is centralized bringing a hierarchical certificate management model with a tree structure and a root. In the context of wireless networks where the trust management should be distributed, the X509 model cannot fit. SPKI provides flexibility for trust management by allowing delegation. However, there is no restriction to control the delegated signature chain or allow the issuer to update the trust value of each delegated certificate. The PGP trust model supports trust management in distributed networks. It uses a trust model that has no centralized or hierarchical relationship between certification authorities as in X.509. The underlying assumption is that trustees may validate digital certificates from other entities or trust a third party to validate certificates. However, entities are fully trusted and there is a need for a mechanism to compute trustworthiness of every trusted or signed key. A degree of trust such as completely trusted, marginally trusted, or untrusted, should be supported.

Following the previous works, a number of automated trust management systems were proposed including PolicyMaker (Blaze, Feigengaum, & Strauss, 1998a) and KeyNote (Blaze, Feigenbaum, & Keromytis, 1998b). The PolicyMaker provides an application independent framework for constructing and validating the security policies. In fact, the security policy is specified by the system, whereby the applications can create their own actions and policies but are not required to do the security

verification themselves. The system is then used to verify whether an action is consistent with a local policy. This system takes as input a set of local policy statements, a collection of credentials, and a string describing the actions to be performed. It evaluates these policies and credentials by verifying whether an action is consistent with the local policy. The output, which is made by a compliance checker, is a positive or a negative response or even a set of additional requirements to be fulfilled to let the actions be permissible.

KeyNote, which is the successor of PolicyMaker, uses the same design principle of assertions and queries. However, it brings an additional enhancement in the trust management engine and supports special language for assertion which allows a simple integration with the compliance checker. Note that the signature verification is performed in the keynote engine making it well-suited for trust management in public-key infrastructure. KeyNote evaluation is performed after receiving a set of local security assertions, a collection of credential assertions, which may represent certificates signed by entities delegating the trust, and a collection of attributes defining an action environment and containing all information relevant to the request.

Guemara-ElFatmi, Boudriga, and Obaidat (2004) proposed a trust management scheme based on the use of the relational calculus, which allows proving and verifying compliance of communication protocols with security policy in the case where the system is based on of use of public key certificates (PKC). The proposed trust management scheme integrates (1) a relational language for modeling entities (e.g., certificates, security policy) and actions (e.g., delegations); (2) a relational calculus for performing proofs; (3) a mechanism for identifying users; and (4) a compliance engine which allows to decide whether an action, which is performed by a principal can be granted or not. The model of trust management uses (1) a set of certificates/request, say X, denoting requests sent for online checks and operations; (2) a set of response returned by online checks, say Y, to represent the acceptance and rejections of requests; and (3) a binary relation from X^+ (the set of words in X) to Y, called the conformance checking relation, where X^+ denote the set of non-empty chains in X. This relation denotes all pairs of the form (C,y) where C is an input chain and y is the related response.

For complex situations, Guemara-ElFatmi et al. (2004) proposed a deductive system denoted by Δ=(Axiom, Rule, W) where W include formula of the first order logic interpreted over X+ and Y and formula of the form "$(C, y) \in R$". An element in Axiom denotes a formula in the form of $(C, y) \in R \wedge \pi(C) \wedge p(y)$ where π and p represent predicates interpreted over X+ and Y, respectively. y stands for the response at time t for an input chain denoted by C. Elements of Rule have equivalence between certificate chains and have the following form:

$$\frac{(C', y) \in R \quad \pi(C, C')}{(C, y) \in R}$$

The previous rule states that if y is a response to chain C' and if C is related to C' through π then y is the response to chain C. As a consequence, a pair (C, y) is in R, at time t, if and only if the formula $(C, y) \in R$ is a theorem in Δ. The form of the axiom denoted previously allows the characterization and computation of R as a least fixpoint of a function. The trust management model takes into consideration several issues including security policy representation, compliance correctness, and system state determination. The system state determination issue, for instance, shows how to reduce the complexity of online checks by letting the server not to remember its past inputs but rather to just remember a summary of past input history. The aforementioned trust management model was validated using three case studies which are anonymous payment system, clinical information system, and distributed firewall system.

Security Policy Specification

To effectively protect themselves from security threats, organizations should define a security policy, which according to the ISO 17799 represents

a document that provides management direction and support for information security. A security policy can be seen as a specification for security solutions and form a conceptual model of them as the specifications do for software. Improving correctness of security policies is thus essential in order to guarantee the security level required by the secured system. Several formal methods can be used to validate whether a security requirement for systems or components are complete, correct, and can be met by the security policy. Examples include model checking, theorem proving, and executable specifications.

In model checking technique, the security policy may be specified using temporal logic formulas which describe how the permissible system transitions may occur and what modification do they introduce to the system. By adding a description of the initial system state, and the set of security properties that should be followed by the security policy (e.g., all users are authenticated within the system), the model checking technique can be used to verify whether the model satisfies the expressed properties. To do so a graph is generated where nodes represent the system states through which the system progresses while edge represent possible transitions which may alter these states. The main drawback of the model checking technique lies in the state explosion problem that must be addressed to cope with non-finite sate specification. Several approaches can be used to defeat such a problem including the use of binary decision diagrams, partial order reduction to reduce the number of interleaving of non-concurrent processes, and abstraction to prove properties on a system after simplifying it. In theorem proving, specification is based on using formalisms such as first-order logic and higher-order logic. To prove that properties are met by the specification, proof techniques such as induction, rewriting, simplification, and decision procedure using can be followed.

The executable security policy (ESP) specification, which is defined by: "a specification whereby security policy is executed on a computer simulating its behavior when interacting with its environment," is a recent technique for security policy validation. In fact, a security policy is validated by comparing the behavior of the related ESP to what is specified in it. The methodology is based on defining the security policy in natural language then translating it to algebraic specification. After, the algebraic specification is then analyzed for syntactic verification purpose, it is translated to an executable language (e.g., S-TLA+ [Rekhis & Boudriga, 2005]) following a set of rules that have to present some properties including completeness and termination. At this level, the executable security policy is run to detect vulnerabilities.

To validate the security policy, the behavior of the executable security policy can be checked using the model checking technique. The satisfaction of the set of invariants in the security policy can be verified during the generation of potential scenarios by the model checker.

CONCLUSION

Ensuring security for wireless networks signifies several goals to achieve including the security of connected mobiles nodes, the security of services provided by wireless nodes and that are accessible from public networks, and the security of exchanged data between wireless nodes. All these goals may be achieved through the use of a set of mechanisms and models that have been the subject of this chapter. Authentication, privacy protection, trust, and security models are the concepts that are detailed in this chapter showing the possible solutions that may be adopted to prevent a set of attacks that represent a potential threat for wireless networks.

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KEY TERMS

Authentication: Authentication is the process of attempting to verify the digital identity of the sender of a communication such as a request to log in. The sender being authenticated may be a person using a computer, a computer itself, or a computer program.

Digital Certificate: Digital certificate is an electronic document which incorporates a digital signature to bind together a public key with an identity—information such as the name of a person or an organization, their address, and so forth. The certificate can be used to verify that a public key belongs to an individual.

Digital Signature: Digital signature is a type of asymmetric cryptography used to simulate the security properties of a signature in digital rather than written form. Digital signature schemes normally give two algorithms, one for signing which involves the user's secret or private key, and one for verifying signatures which involves the user's public key. The output of the signature process is called the "digital signature."

Hash Function: Hash function is a function that takes a long string (or "message") of any length as input and produces a fixed length string as output, sometimes termed a message digest or a digital fingerprint.

Privacy: Privacy is the fact of protecting personal data and information related to a communication entity to be collected from other entities that are not authorized**.** Privacy is sometimes related to anonymity and can be seen as an aspect of security.

Wireless Network: Wireless network refers to any type of network that is wireless, the term is most commonly used to refer to a telecommunications network whose interconnections between nodes is implemented without the use of wires.

Wireless Sensor Network (WSN): WSN is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants at different locations. The development of wireless sensor networks was originally motivated by military applications. However, wireless sensor networks are now used in many civilian application areas.

Chapter XV
The Provably Secure Formal Methods for Authentication and Key Agreement Protocols

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ABSTRACT

In the design and analysis of authentication and key agreement protocols, provably secure formal methods play a very important role, among which the Canetti-Krawczyk (CK) model and universal composable (UC) security model are very popular at present. This chapter focuses on these two models and consists mainly of three parts: (1) an introduction to CK model and UC models; (2) A study of these two models, which includes an analysis of CK model and an extension of UC security model. The analysis of CK model presents its security analysis, advantages, and disadvantages, and a bridge between this formal method and the informal method (heuristic method) is established; an extension of UC security model gives a universally composable anonymous hash certification model. (3) The applications of these two models. With these two models, the four-way handshake protocols in 802.11i and Chinese wireless LAN (WLAN) security standard WLAN authentication and privacy infrastructure (WAPI) are analyzed.

INTRODUCTION

Key agreement protocols are mechanisms by which two parties that communicate over an adversarially controlled network can generate a common secret key. Key agreement protocols are essential for enabling the use of shared-key cryptography to protect transmitted data over insecure networks. As such they are a central piece for building secure communications and are among the most commonly used cryptographic protocols.

The design and analysis of secure key agreements protocols has proved to be a non-trivial task, with a large body of work written on the topic. Among the methods for the design and analysis of key agreement protocols, formal methods have always been a focused problem in the international investigation of cryptography. Over the years, two distinct views of formal methods, symbolic logic method and computational complexity method, have developed in two mostly separate communities (Martin & Phillip, 2002). The symbolic logic method relies on a simple but effective symbolic formal expression approach, in which cryptographic operations are seen as functions on a space of symbolic formal expressions (e.g., BAN, communicating sequential processes [CSP], NRL) (Wenbo, 2004). The other one, computational complexity method, relies on a detailed computational model that considers issues of complexity and probability of successful attacks, in which cryptographic operations are seen as functions on strings of bits.

Provably secure formal method, which is based on the computational complexity method, is a very hot research point at present. Its salient property is that the security protocols designed by them are provably secure. Among the provably secure formal methods, CK model and UC security model are very popular.

In 2001, Canetti and Krawczyk presented the CK model for the formal analysis of key-exchange (KE) protocols. A session-key security definition and a simple modular methodology to prove a KE protocol with this definition are introduced in this model. One central goal of the CK model is to simplify the usability of the definition via a modular approach to the design and analysis of KE protocols. It adopts the indistinguishability approach (Bellare, Canetti, & Krawczyk, 1998) to define security: A KE protocol is called secure if under the allowed adversarial actions it is infeasible for the attacker to distinguish the value of a key generated by the protocol from an independent random value. The security guarantees that result from the proof by the CK model are substantial as they capture many of the security concerns in the real communications setting.

Concurrent composition is a fact of life of real network settings. Protocols that are proven secure in the stand-alone model are not necessarily secure under composition. Therefore, it does not suffice to prove that a protocol is secure in the stand-alone model. UC security model proposed by Canetti in 2001 (Birgit & Michael, 2001) is for representing and analyzing cryptographic protocols under concurrent circumstance (Yeluda, 2003). The salient property of definitions of security in this framework is that they guarantee security even when the given protocol is running in an arbitrary and unknown multi-party environment. An approach taken in this framework is to use definitions that treat the protocol as stand-alone but guarantee secure composition. Security in complex settings (where a protocol instance may run concurrently with many other protocol instances, or arbitrary inputs and in an adversary controlled way) is guaranteed via a general composition theorem. On top of simplifying the process of formulating a definition and analyzing protocols, this approach guarantees security in arbitrary protocol environments, even unpredictable ones that have not been explicitly considered. The abstract level of UC security goes far beyond other security models, therefore, it tends to be more restrictive than other definitions of security. The most outstanding nature of UC framework is its modular design concept: may alone design a protocol, so long as the protocol satisfies the UC security, it can be guaranteed secure while runs concurrently with other protocols.

This chapter focuses mainly on the introduction, analysis, and applications of these two provably secure formal methods. The rest of this chapter is organized as follows. The next section, the CK model and the UC security model are introduced. In the third section, we analyze the security of the CK model. A bridge between this formal method and the informal method (heuristic method) is established. What is more, the advantages and disadvantages of the CK model are given. In the *Universally Composable Anonymous Hash Certification Model* section, an extension of the UC security model is presented. The UC security model fails to characterize the special security requirements of anonymous authentication with

other kind of certificates. Therefore the UC security model is extended, and a new model—Universally Composable anonymous hash certification model is presented. In this model, an anonymous hash certification ideal function is introduced, which fulfills the identity authentication by binding the identity to special hash values. In addition, a more universal certificate CA model is presented, which can issue the certificate with specific form (for example hash value). In the fifth section, we analyze the four-way handshake protocol in 802.11i with the CK model and UC security model. In sixth section, first, the authentication modules in the Chinese WLAN national standard WAPI and its implementation plan are analyzed with the CK model. Then we point out that how the implementation plan overcomes the security weaknesses in the original WAPI. The last two sectionscontain the future trends and conclusions.

BACKGROUND OVERVIEW

Definition 1: Key-agreement protocol (Menezes, Van Oorschot, & Vanstone, 1996). A key-agreement protocol or mechanism is a key establishment technique in which a shared secret is derived by two (or more) parties as a function of information contributed by, or associated with, each of these, (ideally) such that no party can predetermine the resulting value.

The CK model and UC security model are very popular provably secure formal methods for key-agreement protocols at present. In this section, these two security models are introduced respectively, and the relationship between the security definitions in these two models is also given.

The Canetti-Krawczyk Model

A KE protocol is run in a network of interconnected parties where each party can be activated to run an instance of the protocol called a session. A KE session is a quadruple (*A, B, X, Y*) where *A* is the identity of the holder of the session, *B* the peer, *X* the outgoing messages in the session, and *Y* the incoming messages. The session (*B, A, Y, X*) (if it exists) is said to be matching to the session (*A, B, X, Y*). Matching sessions play a fundamental role in the definition of security (Canetti & Krawczyk, 2001).

Attacker Model

The attacker is modeled to capture realistic attack capabilities in open networks, including the control of communication links and the access to some of the secret information used or generated in the protocol. The attacker, denoted M, is an active "man-in-the-middle" adversary with full control of the communication links between parties. M can intercept and modify messages sent over these links, it can delay or prevent their delivery, inject its own messages, interleave messages from different sessions, and so forth. (Formally, it is M to whom parties hand their outgoing messages for delivery.) M also schedules all session activations and session-message delivery. In addition, in order to model potential disclosure of secret information, the attacker is allowed access to secret information via session exposure attacks (a.k.a. known-key attacks) of three types: state-reveal queries, session-key queries, and party corruption.

- **State-reveal query:** A state-reveal query is directed at a single session while still incomplete (i.e., before outputting the session key) and its result is that the attacker learns the session state for that particular session (which may include, for example, the secret exponent of an ephemeral Diffie-Hellman algorithm (DH) value but not the long-term private key used across all sessions at the party).
- **Session-key query:** A session-key query can be performed against an individual session after completion and the result is that the attacker learns the corresponding session key.
- **Party corruption:** Party corruption means that the attacker learns all information in the memory of that party (including the long-term private key of the party as well all session states and session keys stored

at the party); in addition, from the moment a party is corrupted all its actions may be controlled by the attacker. Indeed, note that the knowledge of the private key allows the attacker to impersonate the party at will.

Three Components in CK Model

- **The unauthenticated–links adversarial model (UM):** UM is the real network environment, the attacker in this model is an active one. It has all the attack ability mentioned previously.
- **The authenticated-links models (AM):** The adversarial model called AM is defined in a way that is identical to the UM with one fundamental difference: The attacker is restricted to only delivering messages truly generated by the parties without any change or addition to them.
- **Authenticators:** Authenticators are special algorithms which act as automatic "compliers" that translate protocols in the AM into equivalent (or "as secure as") protocols in the UM. Now there are two kinds of authenticators, one is based on the public key digital signature, the other one is based on the message authentication code (Bellare et al., 1998).

With the CK model, one can firstly design and analyze a protocol in AM, then transforms these protocols and their security assurance to the realistic UM by using an authenticator.

Definition of Session-Key Security

In addition to the regular actions of the attacker $\mathcal{M}$ against a KE protocol π, he/she can perform a *test session query*. That is, at any time during its run, $\mathcal{M}$ is able to choose, a *test-session* among the sessions that are completed, unexpired, and unexposed at the time. Let k be the value of the corresponding session key. We toss a coin b, b $\xleftarrow{R}$ {0,1}. If b = 0 we provide $\mathcal{M}$ with the value k. Otherwise we provide $\mathcal{M}$ with a value r randomly chosen from the probability distribution of keys generated by protocol π. The attacker $\mathcal{M}$ is not allowed state-reveal queries, session-key queries, or party corruption on the test-session or its matching session. At the end of its run, $\mathcal{M}$ outputs a bit b' (as its guess for b).

An attacker that is allowed test-session queries is referred to as a KE-adversary.

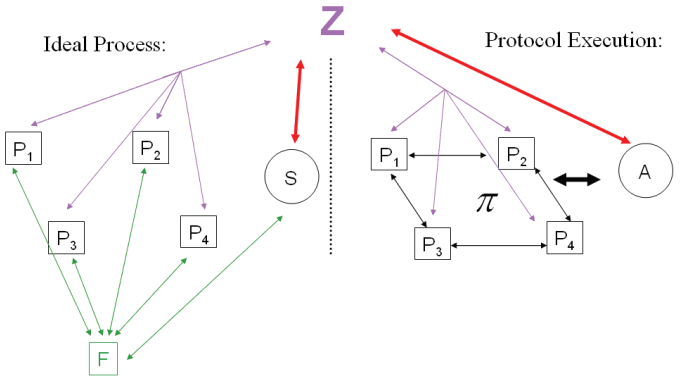
Definition 2: Session-key security. A KE protocol π is called session-key secure (or SK-secure) if the following properties hold for any KE-adversary $\mathcal{M}$:

1. Protocol π satisfies the property that if two uncorrupted parties complete matching sessions then they both output the same key; and
2. The probability that $\mathcal{M}$ guesses correctly the bit b (i.e., outputs b' = b) is no more than 1/2 plus a negligible fraction ε in the security parameter. ε is called "advantage."

The Universal Composable Model

Universally composable security is a framework for defining the security of cryptographic protocols (Canetti, 2001). In this framework, an uncorruptable ideal functionality $\mathcal{F}$ which can provide a certain service, a set of dummy parties $\tilde{P}$ and an ideal adversary $\mathcal{S}$ are defined respectively. Only the dummy parties $\tilde{P}$ and ideal adversary $\mathcal{S}$ can access ideal functionality $\mathcal{F}$, each dummy party can not communicate directly with the others, and the ideal adversary can corrupt any dummy party at any time. The ideal adversary $\mathcal{S}$ is informed of when a message is sent, but not of the content, it is allowed to delay the delivery of such a message, but not change its content. On the other hand, an actual protocol π that can achieve the special service, a set of real parties P, and a real-world adversary $\mathcal{A}$ are correspondingly defined. Each real party can communicate with the others directly and the real-world adversary $\mathcal{A}$ can control all communications among them, meaning that $\mathcal{A}$ can read or alter all messages among the real parties, what is more, $\mathcal{A}$ can also corrupt any real party at any time. An environment Z is defined in the UC framework that can simulate the whole external environment;

Figure 1. The framework of universally composable security



it can generate the inputs to all parties ($\tilde{P}$ or P), read all outputs, and in addition interact with the adversary ($\mathcal{A}$ or $\mathcal{S}$) in an arbitrary way throughout the computation. The environment 9 pt is forbidden to directly access the ideal functionality $\mathcal{F}$.The framework of universally composable security is shown in Figure.1.

Definition 3: Universally composable security (Canetti, 2001). In UC framework, real protocol π securely realizes ideal functionality $\mathcal{F}$ if, for $\forall\mathcal{A}$ and ∀Z, it has the same "action" as $\mathcal{F}$. Formally, a protocol π securely realizes an ideal functionality $\mathcal{F}$ is for any real-life adversary $\mathcal{A}$ there exists an ideal-process adversary $\mathcal{S}$ such that, for any environment Z and on any input, the probability that Z outputs "1" after interacting with $\mathcal{A}$ and parties running π in the real-life model differs by at most a negligible fraction from the probability that Z outputs "1" after interacting with $\mathcal{S}$ and $\mathcal{F}$ in the ideal process.

Definition 4: Composition theorem (Canetti, 2001). The key advantage of UC security is that we can create a complex protocol from already designed sub-protocols that securely achieves the given local tasks. This is very important since complex systems are usually divided into several sub-systems, each one performing a specific task securely. Canetti presented this feature as the composition theorem. This theorem assures that we can generally construct a large size "UC-secure" cryptographic protocol by using sub-protocols which is proven as secure in UC-secure manner.

Definition 5: Hybrid model (Canetti, 2001). In order to state the aforementioned definition and to formalize the notion of an actual protocol with access to multiple copies of an ideal functionality, Canetti also introduced the hybrid model which is identical to the actual model with the following: On top of sending messages to each other, the parties may send messages to and receive messages from an unbounded number of copies of an ideal functionality $\mathcal{F}$. The copies of $\mathcal{F}$ are differentiated using their session identifier SIDs. All messages addressed to each copy and all messages sent by each copy carry the corresponding SID.

The Relationship Between the SK-Security and UC-Security

UC-security is strictly stronger than SK-security. That is, for a KE protocol, UC-security is stronger than SK-security. Any UC-secure key-agreement protocol is SK-secure, but an SK-secure key agreement is not necessarily UC-secure.

Claim 1: Any protocol that is UC-secure is SK-secure. This holds in the UM and in the AM.

Definition 6: Acknowledgment (ACK) property. Let $\mathcal{F}$ an ideal functionality and let π be an SK-secure key protocol in the $\mathcal{F}$-hybrid model. An algorithm *I* is said to be an internal state simulator for π if for any environment machine Z and any adversary $\mathcal{A}$ we have:

$$\mathrm{HYB}^{\mathcal{F}}_{\pi,\mathcal{A},Z} \approx \mathrm{HYB}^{\mathcal{F}}_{\pi,\mathcal{A},Z,I}$$

Protocol π is said to have the ACK property if there exists a good internal state simulator for π.

- **Theorem 1:** Let π be a KE protocol that has the ACK property and is SK-secure; then π is UC-secure (Canetti & Krawczyk, 2002).

SECURITY ANALYSIS OF THE CANETTI-KRAWCZYK MODEL

In the past 20 years, researchers have made a lot of efforts in designing and analyzing KE protocols (Diffie & Hellman, 1976; Diffie, Van Oorschot, & Wiener, 1992; Krawczyk, 1996; Shoup, 1999), they realize that the potential impact of the compromise of various types of keying material in a key-agreement protocol should be considered, even if such compromise is not normally expected (Menezes et al., 1996). So some desirable security properties that a key-agreement protocol should have are identified. Such security properties include perfect forward security (PFS), loss of information, known-key security, key-compromise impersonation, unknown-key share, key control, and so on.

The main goal of the CK model is to design and analyze key-agreement protocols. Then what is the relationship between the CK model and the desirable security attributes for a key-agreement protocol? This is the main motivation of this section.

Properties of Key-Agreement Protocols

Definition 7: (Implicit) key authentication (Menezes et al., 1996). Key authentication is the property whereby one party is assured that no other party aside from a specifically identified second party (and possibly additional identified trusted parties) may gain access to a particular secret key.

A key-agreement protocol, which provides implicit key authentication to both participating entities, is called an *authentication and key-agreement* (*AKA*) protocol.

Definition 8: Key confirmation (Menezes et al., 1996). Key confirmation is the property whereby one party is assured that a second (possibly unidentified) party actually has possession of a particular secret key.

Definition 9: Explicit key authentication (Menezes et al., 1996). Explicit key authentication is the property obtained when both (implicit) key authentication and key confirmation hold.

A key-agreement protocol which provides explicit key authentication to both participating entities is called *authenticated key agreement with key confirmation* (*AKC*) protocol (Menezes et al., 1996).

A secure key-agreement protocol should be able to withstand both passive attacks and active attacks. In addition to implicit key authentication and key confirmation, a number of desirable security attributes of key-agreement protocols have been identified (Law, Menezes, Qu, Solinas, & Vanstone, 1998).

1. **(Perfect) forward secrecy:** If long-term private keys of one or more entities are compromised, the secrecy of previous session keys established by honest entities is not affected (Menezes et al., 1996).
2. **Loss of information:** Compromise of other information that would not ordinarily be available to an adversary does not affect the security of the protocol. For example, in Diffie-Hellman type protocols, security is not comprised by loss of $\alpha^{s_i s_j}$ (where S_i represents entity i's long-term secret value) (Blake-Wilson, Johnson, & Menezes, 1997).
3. **Known-key security:** A protocol is said to be vulnerable to a known-key attack if compromise of past session keys allows either a passive adversary to compromise future session keys, or impersonation by an active adversary in the future (Law et al., 1998).
4. **Key compromise impersonation:** Suppose *A*'s long-term private key is disclosed. Clearly an adversary that knows this value can now impersonate *A*, since it is precisely this value

that identifies *A*. However, it may be desirable that this loss does not enable an adversary to impersonate other entities to *A* (Law et al., 1998).

5. **Unknown key-share:** Entity *A* cannot be coerced into sharing a key with entity *B* without *A*'s knowledge, that is, when *A* believes the key is shared with some entity $C \neq B$, and *B* (correctly) believes the key is shared with *A* (Law et al., 1998).
6. **Key control:** Neither entity should be able to force the session key to a preselected value (Law et al., 1998).

The Relationship Between the CK Model and the Desirable Secure Attributes

- **Theorem 2:** A key-agreement protocol designed and proved secure by the CK model offers almost all the desirable security properties mentioned above except key control (Li, Ma, & Moon, 2005).

The Relationship Between the Security Attributes and the Two Requirements of SK-Security

In the CK model, some security attributes can be ensured by the first requirement of SK-security, while others by the second requirement. In the following, Theorem 3 and Theorem 4 are presented for a detailed explanation:

- **Theorem 3.** The first requirement of SK-security guarantees a protocol to resist impersonation attacks and unknown key-share attacks (Li et al., 2005).

- **Theorem 4.** The second requirement of SK-security guarantees a protocol to offer PFS, known-key security (Li et al., 2005).

It should be noticed that the first requirement is the precondition of SK-security. Only under the consistency condition, does it make sense to investigate the security properties of PFS and known-key security.

Advantages and Disadvantages of the CK Mode

Advantages of the CK Model

Why is the CK Model Applicable for Designing and Analyzing Key-Agreement Protocols?
First, the indistinguishability between the session key and a random number is used to achieve the SK-security of a key-agreement protocol in the AM. If an attacker can distinguish the session key from a random number with a non-negligible advantage, a mathematics hard problem will be resolved. According to the reduction to absurdity, a conclusion can be gotten: no matter what methods are used by the attacker (except party corruption, session state reveal and session key query), he/she cannot distinguish the session key from a random number with a non-negligible advantage. So the protocol designed and proved secure by the CK model can resist known and even unknown attacks.

Second, the CK model employs authenticators to achieve the indistinguishability between the protocol in the AM and the corresponding one in the UM. Through this method, the consistency requirement of SK-security is satisfied.

From the previous analysis, it can be seen that this model is a modular approach to provably secure protocols. With this model, we can easily get a provably secure protocol which can offer almost all the desirable security attributes. And the CK model has the composable characteristic and can be used as an engineering approach (Bellare & Rogaway, 1993; Mitchell, Ward, & Wilson, 1998). Therefore, it is possible to use this approach without a detailed knowledge of the formal models and proofs, and is very efficient and suitable for applications by practitioners.

Disadvantages of the CK Model

Though the CK model is suitable for the design and analysis of key-agreement protocols, it still has some weaknesses as follows:

1. The CK model cannot detect security weaknesses that exist in key-agreement protocols, however some other formal methods have this ability, such as the method based on logic (Burrows, Abadi, & Needham, 1990) and the method based on state machines (Tin, Boyd, & Nieto, 2003). But the CK model can confirm the known attacks, that is, this model can prove that a protocol that has been found flaws is not SK-secure.
2. In the aspect of the forward secrecy, the CK model cannot guarantee that a key-agreement protocol offers forward secrecy with respect to compromise of both parties' private keys; it can only guarantee the forward secrecy of a protocol with respect to one party. In addition, in ID-based systems this model lacks the ability to guarantee the key generation center (KGC) forward secrecy because it does not fully consider the attacker's capabilities (Canetti & Krawczyk, 2002).
3. From Theorem 2, we know that protocols which are designed and proved secure by the CK model cannot resist key control, which is not fully consistent with the definition of key agreement (Blake-Wilson et al., 1997).
4. A key-agreement protocol designed and proved secure by the CK model cannot be guaranteed to resist denial-of-service (DoS) attacks. However DoS attacks have become a common threat in the present Internet, which have brought researchers' attention (Burrows et al., 1990; Meadows, 1996).
5. Some proofs of the protocols with the CK model are not very credible because of the subtleness of this model. For example, the Bellare-Rogaway three-party key-distribution (3PKD) protocol (Bellare & Rogaway, 1995) claimed proofs of security, but it is subsequently found flaws (Choo & Hitchcock, 2005).

We know that a protocol designed and proved secure by the CK model can offer almost all the security attributes, and this model has the modular and composable characteristics, so it is very practical and efficient for the design of a key-agreement protocol. But this model still has weaknesses. So when the CK model is employed to design a key-agreement protocol, we should pay attention to the possible flaws in the protocol that may result from the weaknesses of CK model.

A UNIVERSALLY COMPOSABLE ANONYMOUS HASH CERTIFICATION MODEL

The essence and difficulty of UC security protocol design lays in the formalization and abstraction of a perfect ideal functionality which can be realized securely. We consider the special security requirements for ideal anonymous authentication, define the security notions for them, and realize an anonymous hash certification ideal functionality F_{Cred} in a universally composable security sense, and present a more universal certificate CA model F_{HCA} (Canetti, 2004), which can issue anonymous hash certificates.

Anonymous Hash Certification Ideal Functionality F_{Cred}

We use Merkle tree to build the hash chain, which is constructed from each leaf up to the root of the tree. For each unit of the chain, it contains a value and an order bit which identities whether the given value should be concatenated from the left or the right.

A hash chain is said to be valid under a collision-free hash function H if $h_0 = h_o^{'}$ and $h_{d-1}^{'} = v$, $h_{i-1}^{'} = H(h_i \| h_i^{'}) / H(h_i^{'} \| h_i)$ for $o_i = l/r$, where $i=d\text{-}1,d\text{-}2,\ldots,1$. It is written as $isvalid(h) = 1$. We also define several other functions, for instance, $root(h)$ is to choose the root of a hash chain, $leaf(h)$ is to return the value of a leaf node of path h, $buildtree_H(C)$ is to build a Merkle tree with the values of set C, and $getchain_T(e)$ is to capture the path of node e.

Security Requirements of F_{Cred}

Definition 10. Let k be a security parameter and $\varepsilon(k)$ be a negligible function on k. Let s be a

signature key, *v* be a verification key. We say that an anonymous hash certification protocol satisfies the security requirements if the following properties hold:

Completeness. For any valid credential (*c*, p_i, *k*, *h*),
$Prob[(s,v) \leftarrow gen(1k); 0 \leftarrow Verify\ Credential(c,z,k,p_j,h,\sigma,v)] < \delta(k)$,
where σ is the signature of *root*(*h*).

Consistency. For any valid credential (*c*, p_i, *k*, *h*), the probability that

$$Verify\ Credential(c,z,k,p_j,h,\sigma,v)$$

generates two different outputs in two independent invocations is smaller than ε(*k*).

Unforgeability. For any PPT forger *F*,

$$\text{Prob}[(s,v) \leftarrow gen(1^k); (c,p_j,k,h) \leftarrow F^{\pi_{Cred}}(v), 1 \leftarrow Verify\ Credential(c,z,k,p_j,h,\sigma,v)] < \delta(k)$$

and *F* never as the signature functionality F_{SIG} to sign *root*(*h*).

The Construction of Anonymous Hash Certification Ideal Functionality F_{Cred}

The functionality is realized by using a signature scheme *SS* = (*Kg, Sig,* V_f), a symmetric encryption scheme, a pseudorandom functions *R* and a collision-free, one-way hash functions *H*. we assume that *SS* is CMA secure for the simplified purpose.

In the anonymous hash certification ideal functionality, the entities are denoted as ASU for the authentication server, which is also denoted by P_0 for the simplified purpose, and P_1, ..., P_m for the subscribers or authenticator respectively.

Two security parameters, k_1 and k_2, are used in this ideal functionality. The parameter k_1 is the key length of the symmetric cipher, and k_2 is the length of string used to identify the authenticator. A special function ℓ is used to map the identity of authenticator to $[k_2]$ such that $\ell(p_j)$ has cardinality $k_2/2$, and $\ell(p_i) \neq \ell(p_j)$ for $p_i \neq p_j$.

The credential is denoted as $c_i = (c, p_i, k, h)$, where *c* is the encrypted real identity of the subscriber, P_i is the owner identity of the credential, *k* is the secret information, that is, the hash pre-images, with its length is k_2, *h* is the Merkle hash chain path of this credential. The value of this credential is defined as $val_H(c_i) = c \| H(k_1) \| H(k_2) \| \cdots \| H(k_{k_2})$.

A counter *t* that is initialized to 0 and is used to index credential c_i that has been issued in period *i*. A set of credential $C = \cup c_i$ and a set of credential to be used $T_{prepared}$ are initialized to ϕ.

1. *Present Credential*

Upon receiving a message

$$(Present\ Credential, p_i, c, z, p_j)$$

from some party p_i, send

$$(Present\ Credential, p_i, c, z, p_j)$$

to the adversary. Return the message from the adversary to p_i.

2. *Verify Credential*

Upon receiving a message

$$(Verify\ Credential, p_i, c, z, \tilde{k}, p_j, h', \sigma, v)$$

from some party p_i,

$$(Verify\ Credential, p_i, c, z, \tilde{k}, p_j, h', \sigma, v)$$

send to the adversary. Return the message from the adversary to p_i.

3. Check Reuse

Upon reception of

$$(Check\ Reuse, p_s, c, z, \tilde{k}_1, \tilde{k}_2, p_{j_1}, p_{j2} h, \sigma, v)$$

from some party p_s, execute

$$(Verify\ Credential, p_i, c, z, \tilde{k}, p_j, h', \sigma, v)$$

for *i* = 1, 2.

- If at least one execution returns,

$$(Verify\ Credential, p_s, c, p_{j_i}, invalid)$$

then return

$(Verify\ Credential, p_s, c, p_{j_i}, invalid)$

to p_s.

- If $P_{j_1} = P_{j_2}$ then return,

$(Check\ Reuse, p_s, c, no)$

otherwise return

$(Check\ Reuse, p_s, c, yes)$

to p_s. (end)

Construction of UC-Secure Anonymous Hash Certification Protocol

In this section, we present a simple protocol that realizes F_{Cred} given F_{SIG}, with the aid of ideally authenticated communication with a "trusted anonymous hash certificate authority." This set-up assumption is formalized as an ideal functionality F_{HCA}.

Firstly we modify the definition of F_{SIG} (Canetti, 2004; Michael & Dennis, 2004) as follows.

1. *Key generation*

Upon reception of (*KeyGen*, *P*) from *P*:

- Sends (*KeyGen, P*) to the adversary S.
- After receiving the message (*VerificationKey, P,* θ) from S, records (*P,* θ) and sends (*VerificationKey, P,* θ) to *P.*

2. *Signature generation*

Upon reception of (*Sign, P, m*) from *P*:

- Sends (*Sign, P, m*) to S.
- After receiving the message (*Signature, P, m,* σ) from S, looks for the record $(m, \sigma, \theta, 0)$. If it is found, sends an error message to *P* and halts. Else, sends $(Signature, P, m, \sigma)$ to *P* and then records $(m, \sigma, \theta, 0)$.

3. *Signature verification*

Upon reception of $(Verify, P, m, \sigma, \theta')$ from a verifier *V*:

- Sends $(Verify, P, m, \sigma, \theta')$ to S.
- After receiving the message $(Verify, P, m, \sigma, \theta')$ from S, works as follows.

1. If $\theta' = \theta$ and there exists the record $(m, \sigma, \theta, 1)$, set $f = 1$.
2. If $\theta' = \theta$, *P* has not yet been corrupted by S, and there exists no record such that $(m, \sigma', \theta, 1)$ for $\forall\sigma'$, set $f = 0$.
3. If $\theta' \neq \theta$ and there exists the record (m, σ, θ', f'), set $f = f'$.
4. Else, set $f = \phi$, then records $(m, \sigma, \theta', \phi)$.

- Hands (*Verified, P, m, f*) to *V.* (end)

Then the anonymous hash certificate authority Functionality F_{HCA} is presented as follows.

1. *Key generation*
   Upon reception of the message (*GenerateKey*) from ASU, send (*KeyGen, ASU*) to the adversary *S*, upon receiving (*Verification Key, ASU, encryption key, k*) from *S*, records (*ASU, v, k*) and return (*Verification Key, ASU, v*).
2. *Identity Encryption*
   Upon reception of the message (*Identity encryption, p_i*) from p_i, proceed as follows:
   1. Verify that p_i is in the member list. If not, return (*Not A Member, p_i*) and quit.
   2. Else, send (*Identity encryption, p_i*) to the adversary *S*, receive the encryption identity *c* of p_i, return (*Encrypted identity, p_i, c*).
3. *Credential generation*
   Upon reception of the message (*Credential generation, p_i, (c, p_i, k, z)*) from p_i, send this message to the adversary, and wait for an *OK* from the adversary. Then, Store credential *e* = (*c, p_i, k,* ϕ) into set C_t, return (*S, New Credential, p_i*) and (*p_i, New Credential, c, z*) to *S*.

4. *Build tree*
   Upon reception of the message (*Build tree, ASU*) from *ASU*, set $T \leftarrow buildtree_H(val_H(C_t))$ and modify each credential $e = (c, p_i, k, \phi)$ of C_t into $(c, p_i, k, getchain_T(val_H(e)))$, and send (*Sign, ASU, root*(*T*)) to the adversary *S*. Upon receiving the message (*Signature, ASU, root*(*T*), σ) from *S*, verify that no entry (*root*(*T*), σ, 1) is recorded, if it is, then output an error message to *S* and halt, else record the entry (*root*(*T*), σ, 1), return (*Build Tree, ASU, T,* σ) to *S*, and set $t \leftarrow t + 1$.
5. *Add prepared credential*
   Upon reception of the message (*Add prepared credential,* p_i, (c, p_j)) from p_i, send this message to the adversary, and wait for an *OK* from the adversary. Then, add (c, p_j) in the set $T_{prepared}$ and return *OK*.
6. *Check prepared credential*
   Upon reception of the message (*Check prepared credential,* p_i, (c, p_j)) from p_i, send this message to the adversary, and wait for an *OK* from the adversary. Then, find (c, p_j) in the set $T_{prepared}$, return *OK* if this entry exists.
7. *Check exist of credential*
   Upon reception of the message (*Check exist of credential,* p_i, (c, p_j, k, h)) from p_i, send this message to the adversary, and wait for an *OK* from the adversary. Then, find (c, p_j, k, h) in the set *C*, return *OK* if this entry exists.
8. *Reveal ID*
   Upon reception of the message (*Reveal ID, ASU, c*) from ASU, find a credential (c, p, ·, ·) in set *C*. If no such entry exists, then send (*Reveal ID, ASU, c*) to the adversary *S*. Once the message (c, p) is received from *S*, returning(*Reveal ID, ASU, c, p*).

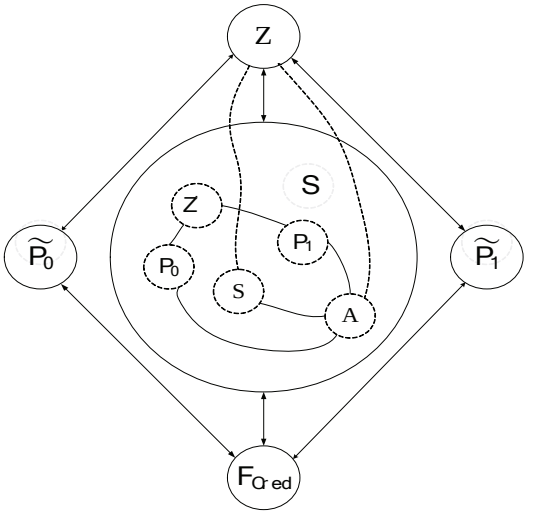
Finally, we present a protocol π_{Cred} that realizes F_{Cred} in the (F_{SIG}, F_{HCA})-hybrid model in a straightforward way as follows.

1. *Present Credential*
   1. p_i receives a message (*Present Credential*, c, z, p_j),
   2. If p_i has not owned a credential, it creates a symmetric key $R^i \xleftarrow{R} R^{k_1}$ with a pseudorandom function and sends (*Identity encryption,* p_i) to F_{HCA}. Upon receiving the message (*Encrypted identity,* p_i, c) from F_{HCA}, it calculates secret information $k_j \leftarrow (R^i(c \| j))_{j=1}^{k_2}$, $z \leftarrow H(k)$, sent (*Credential generation,* p_i, (c, p_i, k, z)) to F_{HCA}.
   3. Else p_i sets $\tilde{k} \leftarrow k_{\ell(P_j)}$ and outputs $(Present\ Credential, c, \tilde{k})$, if $k_l \leftarrow (R^i(c \| l))_{l=1}^{k_2}$ and $z = H(k)$.
   4. Otherwise, it outputs the message (*Reject Present Credential, c*) and quits.
2. *Verify Credentia*l
   1. p_i verifies the validity of $(c, z, \tilde{k}, p_j, h, \sigma, v)$
   2. P_i sends (*Verify* p_i, *root*(*h*), σ, *v*) to F_{SIG} and then executes the signature verification process of F_{SIG}.
   3. P_i sends (*Check prepared credential,* p_i, (c, p_j, p_i)) to F_{HCA}, and wait for an *OK* from F_{HCA}.
   4. P_i verifies $isvalid_H(h) = 1$ and $H(\tilde{k}) = z_{\ell(P_j)}$.
   5. If F_{SIG} returns 0 or any condition 3 or 4 is not satisfied, it returns (*Verify Credential,* p_i, c, p_j, *invalid*) and quits.
   6. else P_i returns (*Verify Credential,* p_i, c, p_j, *valid*).
3. *Check Reuse*
   1. P_i checks the reuse of $(c, z, \tilde{k}_1, \tilde{k}_2, h, \sigma, p_{j_1}, p_{j_2})$,
   2. It executes $(Verify\ Credential, c, z, \tilde{k}_i, h, \sigma, p_{j_i})$ for $i = 1, 2$.
   3. If at least one execution returns (*Verify Credential, c,* p_{ji}, *invalid*), then p_i returns (*Check Reuse, c, invalid*) and quits.
   4. If $p_{j_1} = p_{j_2}$ then p_i returns (*Check Reuse, c, no*), otherwise it returns (*Check Reuse, c, yes*).

Proof of π_{Cred} Securely Realizes F_{Cred} in the (F_{SIG}, F_{HCA})-Hybrid Model

Theorem 5. Protocol π_{Cred} securely realizes F_{Cred} in the (F_{SIG}, F_{HCA})-hybrid model.

Figure 2. The construction of an adversary S



Proof. Let A be an adversary that interacts with entities running π_{Cred} in the (F_{SIG}, F_{HCA})-hybrid model. We construct an ideal-process adversary S such that the view of any environment Z of an interaction with A and π_{Cred} is distributed identically to its view of an interaction with S in the ideal process for F_{Cred}.

1. *The construction of adversary S*

The adversary S runs an internal copy of environment Z, adversary A and each of the involved parties p_i. All messages from Z to A are written to A's input tape. In addition, S does the following: For each player p_i that the real-world adversary A corrupts, the ideal adversary S corrupts the corresponding dummy player p_i. When a corrupted dummy player p_i receives a message m from Z, the adversary S lets Z' send m to p_i. When a corrupted p_i outputs a message m to Z', then S instructs the corrupted p_i to output m to Z. This corresponds to p_i being linked directly to Z. The construction of the adversary S is shown in Figure 2.

2. *The operations of adversary S*

Simulating Present Credential

When S receives in the ideal process F_{Cred} a message (*Present Credential, p_i, c, z, p_j*), it proceeds as follows:

1. If p_i has not owned a credential, then simulate for A the process of credential generation. That is, send to A (in the name of F_{HCA}) the message (*Identity encryption, p_i*), obtain the response from A, then it set a random number u^i as the key of P_i, i.e., $u^i \xleftarrow{R} \{0,1\}^{k_1}$, record (P_i, u^i) in the member list and then calculates secret information $k_j \leftarrow (U^i(c \parallel j))_{j=1}^{k_2}$, $z \leftarrow H(k)$, where $k = (k_1, k_2, ..., k_{k_2})$, and send to A the message (*Credential generation, p_i,* (*c, p_i, k, z*)) from F_{HCA}.
2. Simulate for A the process of present credential. That is, set $m \xleftarrow{R} \{0,1\}^{k_2}$, make sure the number of "1" is exactly $k_2/2$ and m never been produced before, construct the challenge information $k \leftarrow k_m$ by providing the pre-images of secret information k that corresponding to the bit "1" of m, send the message (*Add prepared credential, p_i,* (*c, p_j*)) to A from F_{HCA}, and send $(Present\ Credential, p_i, c, k)$ to F_{Cred}.

Simulating Verify Credential

1. If a message $(Verify\ Credential, p_i, c, z, \tilde{k}, p_j, h', \sigma, v)$ arrives from F_{Cred}, it proceed as follows.
2. Send the message $(Check\ exist\ of\ credential, p_i, (c, p_i, k, h))$ to A from F_{HCA}. If the message from F_{HCA} is not *OK*, send $(Verify\ Credential, p_i, c, p_j, invalid)$ to F_{Cred} and quit.
3. Else check the path, if $h' \neq h$, then send $(Verify\ Credential, p_i, c, p_j, invalid)$ to F_{Cred} and quit.
4. Else, verify the signature, send $(Verify\ p_i, root(h), \sigma, v)$ to A (in the name of) F_{SIG}, upon receiving the message $(Verified\ p_i, root(h), \phi)$ from A,

   (1) If the entity $(root(h), \sigma, 1)$ is recorded, set $f = 1$.

   (2) Else, if the signer is not corrupted, and no entry $(root(h), \sigma', 1)$ for any σ' is recorded, then set $f = 0$ and record the entry $(root(h), \sigma, 0)$.

   (3) Else, if there is an entry $(root(h), \sigma, f')$ recorded , then let $f = f'$.

   (4) Else, let $f = 0$ and record the entry $(root(h), \sigma, \varphi)$.

If $f = 0$, send $(Verify\ Credential, p_i, c, p_j, invalid)$ to F_{Cred} and quit.

5. Else, verify the validity of the credential,

   (1) If p_i is not corrupted,

   (a) Send message $(Check\ prepared\ credential, p_i, (c, p_j))$ to A from F_{HCA}.

   (b)If $\tilde{}$ the F_{HCA} message fromis not *OK* or $k \neq k_m$, send to F_{Cred} the message $(Verify\ Credential, p_i, c, p_j, invalid)$ and quit.

   (2) Else if $H(\tilde{k}) \neq z_m$, send $(Verify\ Credential, P_i, C, P_j, invalid)$ to F_{Cred} and quit.

   Otherwise return $(Verify\ Credential, p_i, c, p_j, valid)$ to F_{Cred}.

Simulating party corruptions

If A corrupts a patty p_i, then S corrupts the same party $\tilde{P}_i$ in the ideal process and hands A the internal data of that party $\tilde{P}_i$.

As for the other operations, like ***Check Reuse***, because their definitions are identical in the ideal functionality and real protocol, it is no use for them to be simulated for A.

As the simulation is perfect and the proof is direct, the proof procedure can be referred to Fan, JianFeng, & Moon, 2007).

THE SECURITY ANALYSIS OF FOUR-WAY HANDSHAKE IN 802.11I WITH THE CK MODEL AND UC MODEL

WLAN can provide great flexibility for the users. However, security is always a serious concern because of the openness of wireless medium for public access within a certain range. To solve the security problems of WLAN, the IEEE 802.11 has designed a new security standard, which is called IEEE 802.11i (IEEE P802.11i D3.0, 2002). In this standard, a concept of robust security network has been proposed. In addition, an authentication mechanism based on EAP/802.1X/RADIUS (Aboba & Simon, 1999; 802.1X-2001, 2001; Rigney, Willens, Rubens, & Simpson, 2000) has been developed to replace the poor open system authentication and shared-key authentication in WEP (Borisov, Goldberg, & Wagner, 2001). As a long-term solution to secure wireless links, the latest IEEE standard 802.11i has been ratified on June 24, 2004.

The four-way handshake (in short, 4WHS) protocol in 802.11i plays a very important role in the authentication and key-agreement process. Some works have been done on its security analysis. In Changhua and Mitchell (2004) the authors analyzed the four-way handshake protocol using a finite-state verification tool and find a DoS attack. The attack involves forging initial messages from the authenticator to the supplicant to produce inconsistent keys in peers. However the repair proposed by the authors involves only a minor change in the

algorithm used by the supplicant and not involves the protocol itself.

In this section, we give a formal analysis of the four-way handshake. The results show that four-way handshake protocol is secure not only in the CK model, but also in the UC security model. So it can be securely used as the basic model of the authentication and key agreement of WLAN.

The Four-Way Handshake Protocol in 802.11i

In 802.11i, once a shared pairwise master key (PMK) is agreed upon between the authenticator and the supplicant, the authenticator may begin a four-way handshake by itself or upon request from the supplicant. The message exchange is shown, at an abstract level, in Figure 3. S represents the Supplicant and A represents the Authenticator; SPA and AA, SNonce and ANonce, represent the message authentication code (MAC) address and nonces of the supplicant and authenticator, respectively; sn is the sequence number; msg1, 2, 3, 4 are indicators of different message types; MICPTK{} represents the message integrity code (MIC) calculated for the contents inside the bracket with the fresh pairwise transient key (PTK). While MAC is commonly used in cryptography to refer to a MAC, the term MIC is used instead in connection with 802.11i because MAC has another standard meaning, medium access control, in networking.

The fresh PTK is derived from the shared PMK through a pseudo random function with output length X (PRF-X), say, PTK = PRF-X(PMK, "Pairwise key expansion" || Min{AA, SPA} || Max{AA, SPA} || Min{ANonce, SNonce} || Max{ANonce, SNonce}), and divided into Key Confirmation Key (KCK), Key Encryption Key (KEK), and Temporary Key (TK). Note that the MIC is actually calculated with KCK, which is only part of PTK.

The Security Analysis of Four-Way Handshake Protocol

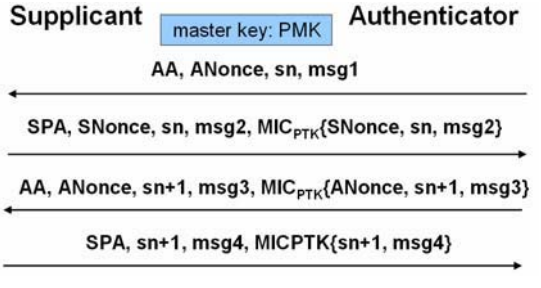
According to the thought of CK model, we extract the protocols $4WHS_{AM}$ in AM and the authenticator λ_{prf}. We can further analyze that whether the protocol $4WHS_{AM}$ is SK-secure in the AM λ_{prf}. or the protocolis an effective MT-authenticator or not, thus we can draw the conclusion that whether four-way handshake protocol can satisfy the definition of SK-security in the UM or not.

Protocol $4WHS_{AM}$

This protocol is described as follows:

1. Both players pre-share a key k_{ij}.
2. The initiator p_i, on input (p_i, p_j, s), chooses $r_i \xleftarrow{R} \{0,1\}^k$ and sends (p_i, s, r_i) to p_j;
3. Upon receipt of (p_i, s, r_i), the responder p_j chooses $r_j \xleftarrow{R} \{0,1\}^k$, where $r_j \neq r_i$, and sends (p_j, s, r_j, t_j) to p_i. Then p_j outputs session key $prf_{k_{ij}}(r_i, r_j)$.
4. Upon receipt of (p_j, s, r_j) player p_j outputs session key $prf_{k_{ij}}(r_i, r_j)$.

Figure 3. The idealized 4-way handshake protocol



The Security Analysis of Protocol $4WHS_{AM}$

Theorem 6. If the pseudorandom function f is secure against chosen message attacks, the protocol $4WHS_{AM}$ is SK-secure without PFS in the AM.

Proof. The protocol $4WHS_{AM}$ is based on a pre-shared key, from which the session key k_{ij} is generated, thus it cannot provide the security attribute of perfect forward security (PFS). According to the model mentioned previously, let the session never expire.

To see that the first requirement of Definition SK-security is satisfied, according to the definition of AM, note that if both p_i and p_j are uncorrupted during the exchange of the key and both complete the protocol, then they both get the uncorrupted r_i and r_j, thus establish the same key, which is $prf_{k_{ij}}$ So the protocol $4WHS_{AM}$ satisfies the property 1of Definition SK-security.

Then we prove that the second property of Definition SK-security is also satisfied by protocol $4WHS_{AM}$. Assume there is a KE-adversary A in the AM against protocol $4WHS_{AM}$ that has a non-negligible advantage δ in guessing correctly b. We can construct an algorithm D that distinguishes pseudorandom and random function with non-negligible probability δ.

Let $Q_0=\{r,t,prf_k(r,t)\}$, and $Q_1=.\{r,t,random\ (\ )\}$ The input to D is denoted by $\{r,t,\gamma\}$ and is chosen from Q_0 or Q_1 each with probability $\frac{1}{2}$. Let L be an upper bound on the number of sessions invoked by A in any interaction. Algorithm D uses adversary A as a subroutine and is described as follows.

1. Choose $m \xleftarrow{R} .\{1,...,l\}$
2. Invoke A, on a simulated interaction in the AM with parties $p_1,...,p_n$ running $4WHS_{AM}$. Each of the parties shares $prf_{k_{ij}}(\ )$ with the other one, except for those two in the m-th session, who share $prf_k(\ )$.
3. Whenever A activates a party to establish a new session (except for the m-th session) or to receive a message, D follows the instructions of $4WHS_{AM}$ on behalf of that party. When a party is corrupted or a session (other than the m-th session) is exposed, hands A all the information corresponding to that party or session as in a real interaction.
4. When the m-th session, say (p_i, p_j, s_m), is invoked within p_i, let p_i send the message (p_i, s_m, r) to p_j.
5. When p_j is invoked to receive (p_i, s_m, r), let p_j send the message (p_j, s_m, t) to p_i.
6. If session (p_i, p_j, s_m) is chosen by A as the test–session, then provide A with γ as the answer to this query.
7. If the m-th session (p_i, p_j, s_m) is ever exposed, or if a session different than the m-th session is chosen as the test–session, or if A halts without choosing a test-session then D outputs $b' \xleftarrow{R} \{0,1\}$ and halts.
8. If A halts and outputs a bit b', then D halts and outputs b' too.

The run of A by D (up to the point where A stops or D aborts A's run) is identical to a normal run of A against protocol $4WHS_{AM}$.

Consider the first case in which the m-th session is chosen by A to be tested and A get the response of γ. Thus, if the input to D came from Q_0 then the response was the actual value of the key. On the other hand, if the input to D came from Q_1 then the response to the test query was a random value. AS mentioned above, the input to D was chosen with probability 1/2 from Q_0 and Q_1. Then the distribution of responses provided by D to the test query of A is the same as specified by Definition SK-security. In this case, the probability that A guesses correctly whether the test value was "real" or "random" is $1/2+\delta$ for a non-negligible value δ. This is equivalent to guessing whether the input to the distinguisher D came from Q_0 or, Q_1 respectively. Thus, by outputting the same bit b' as A, we get that the distinguisher D guesses correctly the input distribution Q_0 or Q_1 with the same probability $1/2+\delta$ as A did.

Now consider the second case in which (p_i, p_j, s_m) is not chosen by A. In this case, D always halts and outputs a random bit, thus its probability to guess correctly the input distribution Q_0 or Q_1 is 1/2.

Since the first case happens with probability $\frac{1}{L}$,

while the second case happens with probability $1-\frac{1}{L}$,

the overall probability of D to guess correctly is

$$PR= (0.5+\delta) + \frac{1}{L}+ 0.5 \times (1-\frac{1}{L})= 0.5+\frac{\delta}{L}$$

Thus D succeeds in distinguishingfromwith non-negligible advantage, which is conflict to the Assumption that the *pseudorandom function is secure*. So the protocol $4WHS_{AM}$ satisfies the property 2 of Definition SK-security.

Thus the protocol $4WHS_{AM}$ is SK-secure without PFS in the AM. #

Authenticator λ_{prf}

Theorem 7. Assume that the pseudorandom function and MAC in use are secure against chosen message attacks. Then protocol λ_{prf} emulates protocol MT in unauthenticated networks. (Fan et al., 2007).

The Security Analysis of Four-Way Handshake Protocol in the UM

We have proved that the protocol $4WHS_{AM}$ is SK-Secure without PFS in the AM, and the protocol λ_{prf} is a MT-Authenticator, thus we get the result of security analysis of 4WHS in the UM.

Theorem 8. If the pseudorandom function and MAC function in use are secure against chosen message attacks, protocol four-way handshake is SK-Secure in the UM.

The Four-Way Handshake Protocol is UC-Secure

We have proved that 4WHS is SK-secure. According to Definition 6, now we prove that it has the ACK property, thus also satisfies the definition of UC-secure.

Theorem 9. The protocol 4WHS has the ACK property.

Proof. To prove the ACK property for 4WHS we construct the following internal state simulator *I*. Recall that before 4WHS actually generates output, the local state of the first party (p_i in the aforementioned description) consists of (k_1, k_2,s, p_i, p_j). The internal state of the other party (p_j in the aforementioned description) is identical (its internal state, like k_0, has been erased). The output of *I*, given (k_1, s, p_i, p_j) will be $l\,p_i$=$l\,p_j$=(k_1, r_1, s,p_i, p_j), where r_1 is a random value of the same length as k_2. (Consequently, when the internal states of p_i and p_j are replaced with $l\,p_i$ and lp_j respectively, the added protocol message will be computed and verified as MAC_{R_i} (s, r_i) rather than MAC_{K_2} (s, r_i). Next we proof that *I* is a good internal state simulator.

Le *F* be an ideal functionality which can securely realize key exchange and *A* be an adversary. If *I* is not a good internal state simulator, then the environment Z can distinguish between an interaction with *A* and 4WHS and an interaction with *A* and the above transformed protocol(replace the internal states of p_i and p_j with the outputs of *I*) with a non-negligible advantage . The only difference between the protocol resultant from the aforementioned transformation and 4WHS is the replacement of k_2 with r_1. So if *I* is not a good internal state simulator, then Z can distinguish between r_1 and k_2 with a non-negligible advantage. If the adversary can distinguish between $k_2$and a random value with a non-negligible advantage, where k_2=$\sec ond_{n_2}(k_0)$, then he/she can distinguish between k_0 and a random value with a non-negligible advantage. As we have proved that 4WHS is SK-secure, thus the adversary cannot distinguish between k_1 (k_1= $first_{n_1}(k_0)$) and a random value with a non-negligible advantage, well then he/she cannot distinguish between k_0 and a random value with a non-negligible advantage, which reaches a contradiction. So the environment Z cannot distinguish between an interaction with (*A*, 4WHS) and (*A*, the transformed protocol) with a non-negligible advantage, thus we have

$HYB^F_{\pi,A,Z} \approx HYB^F_{\pi,A,Z,I}$ and *I* is a good internal state simulator for 4WHS. According to Definition 6 and theorem 1, we know that 4WHS has the ACK property and is UC-secure. #

According to Theorems 8, 9, and 1, we get Theorem 10.

- **Theorem 10:** If the pseudorandom function and MAC function in use are secure against chosen message attacks, protocol four-way handshake is UC-Secure. #

THE SECURITY ANALYSIS OF CHINESE WLAN SECURITY STANDARD WAPI WITH THE CK MODEL

The Chinese WLAN standard WAPI (GB 15629.11-2003) (National Standard of the People's Republic of China, 2003), the first issued Chinese standard in the field of WLAN, has been formally implemented since November 1, 2003. WAPI is composed of two parts: WAI and wireless privacy infrastructure (WPI). They realize the identity authentication and data encryption, respectively. In March of 2004, China IT Standardization Technical Committee drafted out a new version, WAPI implementation plan (National Standard of the People's Republic of China, 2004), which improves the original standard WAPI. Compared with the original standard, the greatest change the implementation plan made lies in the WAI module.

As a national standard which is about to be deployed and implemented on a large scale, its security is undoubtedly the focus. But as far as we know, up to now, there are no articles that systemically analyze the security of WAPI and its implementation plan, which is imperfect for a national standard. This contribution discusses the security of WAPI and its implementation plan with the CK model. It has three contributions: (1) the security weaknesses of WAI in WAPI are given; (2) the WAI module in the implementation plan is proved secure in the CK model; and (3) how the implementation plan overcomes the security weaknesses of the original WAPI is pointed out. The analysis results can help us understand the necessity of the implementation plan and enhance the confidence of it. At the same time, as a case study, their analysis is helpful for the design of a secure key-agreement protocol.

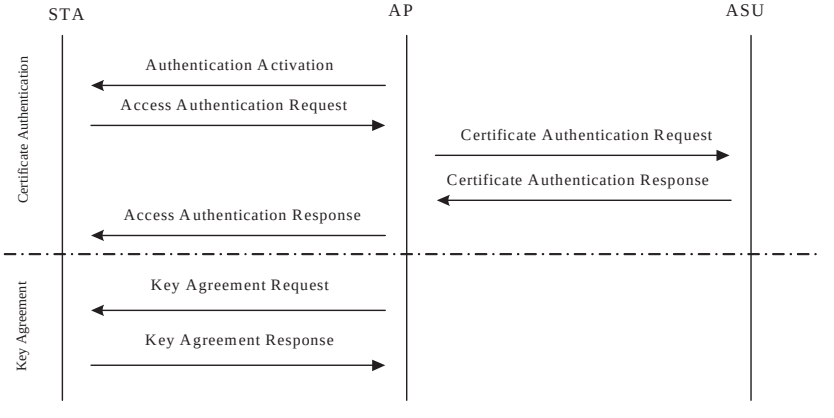
WAIs in WAPI and its Implementation Plan

WAI adopts port-based authentication architecture that is identical with IEEE 802.1X. The whole system is composed of mobile guest STA, access point (AP), and authentication service unit (ASU).

WAI in WAPI

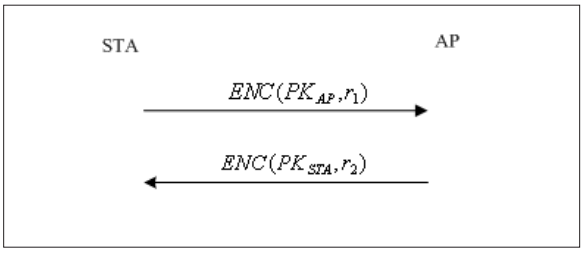
The interaction procedure of WAI in the original national standard WAPI is shown in Figure 4. From this figure, we can see that WAI is composed of two parts: certificate authentication and key agreement.

Figure 4. WAI in WAPI



1. **Certificate authentication.** In this process, station (STA) sends its public key certificate and access request time to the access point (AP) in the access authentication request. AP sends its certificate, STA's certificate, STA's access request time, and its signature on them to authentication service unit (ASU) in certificate authentication request. After ASU validates AP's signature and the two certificates, it sends the certificates validation result, STA's access request time, and ASU's signature on them to STA and AP.
2. **Key agreement.**

Figure 5. The key agreement in the WAI of WAPI



First, STA and AP negotiate the cryptography algorithms. Then, they respectively generate one random value r_1 and r_2. These random values are encrypted with the peer's public key and sent to each other. Both parties decrypt the encrypted random values and derive the session key $K=r_1 \oplus r_2$. The key agreement process is shown in Figure.5, where $ENC(\ )$is the encryption function, PK_{AP} and PK_{STA} are AP and STA's public key respectively.

WAI in the Implementation Plan

In the framework, WAI in the implementation plan is the same as that of the original WAPI, and it is also composed of certificate authentication and key agreement. Compared with the original standard WAPI, the implementation plan remains unchanged in the certificate authentication, but makes rather big improvement in the key agreement. The new key-agreement protocol is shown in Figure.6. It is different from the original one in the following points:

1. In the implementation plan, the key agreement request has to be initiated by AP. At the same time, the secure parameter index SPI, AP's signature on the encrypted random value and SPI are included in this request. The signature algorithm is ECDSA.
2. In the key agreement response, SPI and the STA's MAC on encrypted random and SPI are included. The MAC is computed through HMAC-SHA256 algorithm.
3. The keys derivation method is different. STA and AP first calculate the host key $k= r_{11} \oplus r_2$, then extend k with KD-HMAC-SHA256 algorithm to get the session key k_d, the authentication key k_a and integration check key.

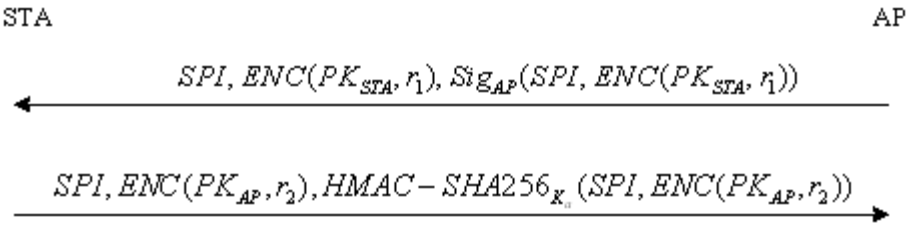
The Security Weaknesses of WAI in WAPI

The WAI module in the original WAPI has several security weaknesses as follows:

1. **Its key-agreement protocol cannot resist the unknown key-share (UKS) attack (Burton & Kaliski, 2001).**

We assume that an attacker E gets a certificate where his/her public key PK_E is same as PK_{STA}. (In many practical settings, the certificate authority [CA] does not require a proof-of-possession of the corresponding private key from a registrant of a public key (Krawczyk, 2005), so an attacker E can get a certificate from the CA in which his/her public key is same as STA's.) In addition, in the certificate authentication process, ASU just verifies the authenticity and validity of a certificate, so E also can pass the certification authentication. Then he/she can launch the unknown-key share attack in the key agreement. When STA sends the first message $ENC(PK_{AP}, r_1)$, E forwards this message to AP and claims that this message is from E. Then AP replies with $ENC(PK_E, r_2)$. E forwards this message to STA. When the protocol completes, STA thinks that he/she agreed upon a key with AP, while AP thinks that he/she negotiated a key with E. And these two keys are same. So, the attacker E succeeds in the UKS attack.

Figure 6. The key-agreement protocol in WAI of the implementation plan



SPI=the MAC of the STA||the BSSID of the AP||the time of authentication request

Let us analyze this attack in the CK model. In the previous attack, the KE-adversary chooses the session in STA as the test session and expose the session in AP (because these two sessions are not matching sessions, the session in AP can be exposed). Because STA and AP get a same session key, the KE-adversary can completely get the session key of the test session. According to Definition 2, this protocol is not SK-secure. And Diffie et al. (1992) can be referred to for the consequences of this attack.

2. **Its key agreement protocol cannot resist key-compromise impersonation (KCI) attack.**

Let us analyze this attack in the CK model. First, we assume that STA's private key is compromised and the attacker chooses the session in STA as the test session after STA complete the matching sessions with AP. The attacker can first corrupt another mobile guest STA' and impersonates him/her to send message $ENC(PK_{AP}, r_1)$ to AP. We denote the session between STA' and AP as SID'. When AP receives this message from STA', he/she chooses another random value r_3 and responds with $ENC(PK_{STA'}, r_3)$. AP computes its session key of SID' $k'= r_1 \oplus r_3$. The attacker can expose this session and get k' (this session is not the matching session of the test session). In addition, the attacker can decrypt $ENC(PK_{STA'}, r_3)$ to get r_3. Thus he/she can get $r_1= k' \oplus r_3$. In addition, the attacker can also decrypt $ENC(PK_{STA}, r_2)$ to get r_2 . Then he/she can get the session key of the test session: $k=r_1 \oplus r_2$. Thus the attacker can impersonate AP to STA. According to Definition 2, this protocol is not SK-secure.

3. **It does not realize the explicit identity authentication of STA and perhaps lead to the faulty charge.**

From the WAI process, we can see that it does not realize the explicit identity authentication of STA to AP. An attacker can pass the certificate authentication and access the networks only if he/she gets a legal user's certificate, which will lead to the faulty charge if the networks charge the fee according to the access time.

The Security Analysis of WAI in the Implementation Plan

In the certificate authentication, AP makes signature in the certificate authentication request, and ASU makes signature in the certificate authentication response. Both these signatures include STA's access request time which ensures the freshness of the signatures. Therefore ASU can authenticate AP's identity and STA can authenticate ASU's identity. In addition, STA trusts ASU. So STA can authenticate the identity of AP after the certificate authentication. At the same time, AP authenticates the certificate provided by STA.

The key-agreement protocol in WAI of implementation plan is denoted by π. In the following,

we will prove that π is SK-secure without PFS (Güther, 1990). That is, the protocol is SK-secure, but does not provide perfect forward secrecy of the session keys. In order to prove that π is SK-secure, we define a "game" as follows.

The Design of an Encryption Game

Let (*G, ENC, DEC*) be a key-generation, encryption and decryption algorithm, respectively, of a public-key encryption scheme that is secure against CCA2 attack (Wenbo, 2004). Let *K* be the security parameter. STA and AP have invoked *G*(*K*) to get their public and private key pairs.

This game integrates the CCA2-security of *ENC* with the key-agreement protocol (Canetti & Krawczyk, 2001; Wenbo, 2004). We will proceed to show that if an attacker can break the SK-security of π, then he/she can win the game, that is, he/she can break the CCA2-security of *ENC*.

The two participants in the game are $\mathcal{G}$ and $\mathcal{B}$ (for good and bad). $\mathcal{G}$ is the party against which $\mathcal{B}$ plays the game. $\mathcal{G}$ acts as a decryption oracle. $\mathcal{G}$ possesses a pair of public and private keys, PK_{STA} and SK_{STA} (generated via the key generation algorithm $\mathcal{G}$). $\mathcal{B}$ is the attacker of protocol π, he/she knows PK_{STA} but not SK_{STA}. He/she leverages the abilities he/she gets in the attack of π to take part in this game. The game process is shown in the following:

Phase 0: $\mathcal{G}$ provides $\mathcal{B}$ with a challenge ciphertext $c^*=ENC(PK_{STA},r_1)$ for $r_1 \xleftarrow{R} \{0,1\}^K$.

Phase 1: $\mathcal{B}$ sends a triple (*c, r, t*) to $\mathcal{G}$ who responds with HMAC-$SHA256_{k_a}(t)$.

($k_a' = last(\text{KD-HMAC-SHA256}(k'))$, $k' = r \oplus r', r' = DEC(SK_{STA}, c)$. The *last*( ) is a function that extract out the last 16 bytes from a bit string.) This is repeated a polynomial number of times with each triple being chosen adaptively by $\mathcal{B}$ (i.e., after seeing $\mathcal{G}$'s response to previous triple), but he/she keeps *r* unchanged in every triple.

Phase 2: $\mathcal{B}$ sends a test string $t^*=(\text{SPI}\|PK_{AP}(r))$ to $\mathcal{G}$. Then $\mathcal{G}$ chooses a random bit

$b \xleftarrow{R} \{0,1\}$. If $b=0$ then $\mathcal{G}$ responds with $\text{HMAC-SHA256}_{k_a''}(t^*)$where $k_a'' = last$

(KD-HMAC-SHA256(k'') , $k'' = r_1 \oplus r$, r_1 is the value encrypted by $\mathcal{G}$ in phase 0. If $b=1$ then $\mathcal{G}$ responds with a random string s^* of the same length as $\text{HMAC-SHA256}_{k_a'}(t^*)$.

Phase 3: Same as Phase 1.

Phase 4: $\mathcal{B}$ outputs a bit b' as the guess of *b*.

And the winner is… $\mathcal{B}$ if and only if $b=b'$.

The following notes are made about the game:

1. The challenging ciphertext c^* in the phase 0 is also the ciphertext sent by AP in the key agreement request of π.
2. In Phase 1, $\mathcal{B}$ randomly chooses a test ciphertext *c*, random value *r* and string *t*, and sends them to $\mathcal{G}$ for process. It should be noticed that $\mathcal{B}$ cannot simultaneously chooses c^* and t^* as the input of $\mathcal{G}$.
3. $\mathcal{B}$ keeps *r* unchanged in every triple in order to reduce the difficulty of the attack.

Security Analysis of Key-Agreement Protocol in WAI

According to Definition 2, in order to prove that π is SK-secure, we have to argue that it can meet two requirements. The first one is that STA and AP can get a same session key after they complete matching sessions. The second one is that $\mathcal{B}$ cannot distinguish the session key k_d from a random value with a non-negligible advantage. In the following, we will prove that π can meet these two requirements.

Lemma 1. *If the encryption scheme ENC is secure against the CCA2 attack, then at the end of protocol* π, *STA and AP will complete matching sessions and get a same session key.*

Proof. Since the signature algorithm ECDSA is secure against existential forgery by adaptive chosen-message attack (Brown, 2001), in addition, SPI in the key agreement request can guarantee the freshness of this message and bind this message with the two communication parties, the attacker cannot forge or modify the request message.

In addition, the attacker $\mathcal{B}$ cannot forge a key agreement acknowledgment message. Let us prove this with the reduction to absurdity. It is assumed

that the attacker can forge an acknowledgment message with a non-negligible probability during the run of the protocol π. That is, he/she can choose a random value (say r_3) and forge a message authentication code that AP can validate. Then $\mathcal{B}$ takes advantage of this ability to run the game above. In Phase 1, he/she also chooses r_3 as the random value r in the triple, while selects c and t randomly. Then, in Phase 2, he/she can work out $\text{HMAC-SHA256}_{k_a''}(t^*)$ because this value is same as the forged message authentication code in the key agreement acknowledgment. Therefore the attacker can distinguish $\text{HMAC-SHA256}_{k_a''}(t^*)$ from s^* and guess correctly b in Phase 4, thus $\mathcal{A}$ wins the game, which indicates that the encryption scheme is not CCA2-secure. This contradicts with the presupposition. So during the run of the protocol π, the attacker cannot forge a key agreement acknowledgment with a non-negligible probability.

Therefore STA and AP will complete matching sessions and get a same session key at the end of protocol π, if ENC is CCA2-secure. #

Lemma 2. *If the encryption scheme ENC is secure against the CCA2 attack, the attacker cannot distinguish the session key k_d from a random value with a non-negligible advantage.*

Proof. It is assumed that the attacker $\mathcal{B}$ can distinguish the session key k_d from a random value with a non-negligible advantage η_1. In the CK model, the KE-attacker is not permitted to corrupt the test session or its matching session, so the attacker $\mathcal{B}$ cannot directly get the session key k_d from the attack of π. While k_d=*first*(KD-HMAC-SHA256(k)) (The *first*( ) is a function that extracts out the first sixteen bytes from a bit string), so the attacker $\mathcal{B}$ has only two possible methods to distinguish k_d from a random value. The first one: $\mathcal{B}$ learns k. The second one: $\mathcal{B}$ succeeds in forcing the establishment of a session (other than the test session or its matching session) that has the same key as the test session. In this case $\mathcal{B}$ can learn the test session key by simply querying the session with the same key, and without having to learn the value k. In the following, we prove that neither of these two methods is feasible.

The first method means that, from the attack of π, the attacker can distinguish $k''= r_1 \oplus r$ from a random value with a non-negligible advantage. Based on this ability, $\mathcal{B}$ also can distinguish $k'' = r_1 \oplus r$ from a random value with a non-negligible advantage. This is because r in the k'' is selected by the attacker himself, which makes the difficulty that he/she distinguishes k'' from a random value no bigger than that he/she distinguishes k from a random value. It is assumed that the advantage that $\mathcal{B}$ distinguishes k'' from a random value is η_2, then $\eta_2 \geq \eta_1$. And because $k_a'' = last$(KD-HMAC-SHA256(k'')), $\mathcal{B}$ can get k_a''. Further, he/she can work out $\text{HMAC-SHA256}_{k_a''}(t^*)$ with a non-negligible probability, which enables the attacker to win the encryption game. That means the encryption scheme is not secure against CCA2 attack. This contradicts the presupposition. So the attacker $\mathcal{B}$ can not get k with a non-negligible probability. Then this method is not practical.

As for the second method, there are two strategies that the attacker can take. (1) After STA and AP complete the matching sessions, the attacker $\mathcal{B}$ establishes a new session with AP or STA. But the session key of this session will not be k_d, because the encrypted random value is chosen randomly by AP or STA. (2) When AP and STA perform the key agreement, $\mathcal{B}$ intervenes this negations and makes them get a same session key without the completion of the matching sessions. That is, STA and AP get a same session key but they do not complete matching sessions. Then the attacker can get the test session key by breaking the unmatching session that has the same session key. But from Lemma 1, we know that if the encryption scheme ENC is secure against the CCA2 attack, $\mathcal{B}$ cannot succeed in this intervention. So this method is not feasible either.

Let us sum up the previous analysis. The attacker $\mathcal{B}$ neither can get the host key k, nor can he/she force to establish a new session with STA or AP that has the same session key as the test session. So the attacker cannot distinguish the session key k_d from the random value with a non-negligible advantage. #

Theorem 11. *If the encryption scheme ENC adopted is secure against CCA2 attack, then π is SK-secure without PFS.*

Proof. According to Lemma 1 and Lemma 2, we know that STA and AP will get a same session key after the key agreement and the attacker cannot distinguish the session key from a random value with a non-negligible advantage. Then in accordance with Definition 2, the protocol π is SK-secure.

In addition, if the private keys of STA and AP are compromised, the attacker can get the random values exchanged and can work out all the session keys that have been agreed about. Thus this protocol cannot provide PFS. So we can get that the key-agreement protocol is SK-secure without PFS. #

The Implementation Plan Overcomes the Weaknesses of the Original WAPI

We know that WAI in the original WAPI has some security weaknesses. But WAI in the implementation plan is secure in the CK model, and according to Li et al. (2005), we get that the WAI module of the implementation plan can resist KCI attack and UKS attack. In the following, we will analyze how the implementation plan overcomes the security weaknesses in the original WAPI.

1. The key-agreement protocol in the implementation plan can resist UKS attack. In the implementation plan, even though the attacker $\mathcal{B}$ gets a certificate in which his/her public key is the same as STA's or AP's, he/she cannot launch the UKS attack. Because the implementation plan requires that the key agreement request be sent by AP, STA just accepts the request from AP. So, $\mathcal{B}$ can just launch the UKS attack against the AP (i.e., AP thinks that he/she agrees upon a key with $\mathcal{B}$, but in fact he/she negotiates a key with STA, while STA correctly thinks that he/she negotiates a key with AP), that is, $\mathcal{B}$ just can forward the key agreement request message for him/her to STA. But in this request, AP's signature includes SPI which includes the MAC address of the $\mathcal{B}$, so STA will not accept this request forwarded from $\mathcal{B}$. Therefore the key-agreement protocol in WAI of implementation plan can resist the UKS attack.

From the previous analysis, we can see that the essential reasons that WAI in the implementation plan can resist the UKS attack are that: (1) the implementation plan requires that the key agreement request be sent from AP; (2) AP's signature includes SPI which includes the destination entity's address.

2. The key-agreement protocol in the WAI of the implementation plan can resist the KCI attack. KCI attacks for the protocol π have two manners. The first one is that AP's private key is compromised and the attacker can impersonate STA to AP. The second one is that STA's private key is compromised and the attacker can impersonate AP to STA. In the following, we will discuss these two cases respectively.

If AP's private key is compromised, the attacker can decrypt $ENC(PK_{AP}, r_2)$ to get r_2. In order to get r_1, he/she just has two possible methods: (1) attacks the encryption algorithm *ENC*; and (2) impersonates other entity to establish another session with STA, and sends $ENC(PK_{STA},r_1)$ to STA, then the attacker exposes this session and gets r_1 through some computations. But neither of these two methods is feasible. For the first method, we know that if the encryption algorithm *ENC* is CCA2 secure, the attacker cannot get r_1 from the attack of this algorithm directly. As for the second method, the implementation plan requires the key agreement request be sent by AP, and the attacker cannot forge AP's signature, so the attacker cannot impersonate other entity to establish another session with STA. Therefore the attacker cannot get r_1. Then he/she still cannot get the host key k and session key k_d .

If STA's private key is compromised, the attacker can decrypt $ENC(PK_{STA},r_1)$ to get r_1. In order to get session key r_2, he/she just has two possible methods: (1) attacks the encryption algorithm *ENC* directly to get r_2; and (2) impersonates another mobile guest STA' to establish a new session with AP and sends it $ENC(PK_{AP}, r_2)$ in the key agreement acknowledgement. From the previous analysis we get that the first method is infeasible. As for the second method, because r_2 and the host key k are just the ephemeral values, we assume that they are not the session states of AP. Therefore, the session states of the new session in AP are just the session key k_d^*, the message authentication key k_a^* and the

message integration key. The attacker cannot get any information about r_2 from these session states because these three keys are the hash values of the host key k^*. Therefore the attacker cannot get r_2 either. (If the session key is not the hash value of k^*, the attacker can get k^*, futher can get r_2.) So the attacker still cannot get the host key *k* and the session key k_d.

As a whole, the essential reasons that the key-agreement protocol can resist KCI attack are that: (1) the implementation plan requires that the key agreement request be sent by AP; and (2) the session key in the implementation plan is derived through the hash function.

(3) The WAI module in the implementation plan realizes the mutual explicit identity authentication between STA and AP, which can withstand faulty charge. For AP, π is an explicit key authentication protocol. So AP can authenticate the identity of STA at the end of WAI. At the same time, STA can authenticate the identity of AP in the certificate authentication. Therefore WAI in the implementation plan realizes the mutual explicit identity authentication between AP and STA. Therefore it can withstand faulty charge.

FUTURE TRENDS

In the future, possible research "hot" points in formal analysis of key-agreement protocol include: (1) decrease in the basic assumptions of the protocol, such as the "perfect" cryptography assumptions, free encryption assumptions; such that the theory research is closer to the practice; (2) extension of the protocol analysis scope; (3) enhancement of the analysis capability of "protocol composition," which is the "hot" and difficult point; (4) integration of the characters of different analysis methods, such as the comparison and combination of CSP model, string space model, model check method, and linear logic methods; (5) the research in automatic generation and check of security protocol; (6) the research in the case that the party number is indefinitely increased; (7) solution to "state exploration" problem in the model check methods; and (8) the research in new areas, such as the DoS attack.

CONCLUSION

In this chapter we focused on the provably secure formal methods for the key-agreement protocols, especially the CK model and universally composable security model. First, these two models are introduced; then we gave a study of these two models. An analysis of CK model presented its security analysis, advantages, and disadvantages, and a bridge between this formal method and the informal method (heuristic method) is established; an extension of UC security model gives a universally composable anonymous hash certification model. Next, with the four-way handshake protocol in 802.11i and the Chinese WLAN security standard WAPI, we give the application of these two models. At last, the future trend of formal analysis method of key-agreement protocol was presented.

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KEY TERMS

Acknowledgment (ACK) property: Let $\mathcal{F}$ an ideal functionality and let π be an SK-secure KE protocol in the $\mathcal{F}$-hybrid model. An algorithm I is said to be an internal state simulator for π if for any environment machine Z and any adversary $\mathcal{A}$ we have $\mathrm{HYB}^{F}_{\pi\,\pi,A,Z} \approx \mathrm{HYB}^{F}_{\pi,A,Z,I}$

Protocol π is said to have the ACK property if there exists a good internal state simulator for π.

Composition Theorem: The key advantage of UC security is that we can create a complex protocol from already designed sub-protocols that securely achieves the given local tasks. This is very important since complex systems are usually divided into several sub-systems, each one performing a specific task securely. Canetti presented this feature as the composition theorem (Canetti, 2001). This theorem assures that we can generally construct a large size "UC-secure" cryptographic protocol by using sub-protocols which is proven as secure in UC-secure manner.

Explicit Key Authentication: Explicit key authentication is the property obtained when both (implicit) key authentication and key confirmation hold.

(Implicit) Key Authentication: (Implicit) key authentication is the property whereby one party is assured that no other party aside from a specifically identified second party (and possibly additional identified trusted parties) may gain access to a particular secret key.

Key-Agreement Protocol: A key-agreement protocol or mechanism is a key establishment technique in which a shared secret is derived by two (or more) parties as a function of information contributed by, or associated with, each of these, (ideally) such that no party can predetermine the resulting value.

Key Confirmation: Key confirmation is the property whereby one party is assured that a second (possibly unidentified) party actually has possession of a particular secret key.

Session-Key Security: *A KE protocol* π *is called Session-key secure (or SK-secure) if the following properties hold for any KE-adversary* M:

1. *Protocol* π *satisfies the property that if two uncorrupted parties complete matching sessions then they both output the same key; and*

2. *The probability that* $\mathcal{M}$ *distinguishes the session key from a random value is no more than 1/2 plus a negligible fraction* ε *in the security parameter.* ε *is called "advantage".*

Universally Composable (UC) Security: In UC framework, real protocol π securely realizes ideal functionality if $\mathcal{F}$, for $\forall$ $\mathcal{A}$ and $\forall$ $\mathcal{Z}$, it has the same "action" as $\mathcal{F}$,. Formally, a protocol π securely realizes an ideal functionality $\mathcal{F}$ is for any real-life adversary $\mathcal{A}$ there exists an ideal-process adversary $\mathcal{S}$ such that, for any environment $\mathcal{Z}$ and on any input, the probability that $\mathcal{Z}$ outputs "1" after interacting witha $\mathcal{A}$ and parties running π in the real-life model differs by at most a negligible fraction from the probability that $\mathcal{Z}$ outputs "1" after interacting with $\mathcal{S}$ and $\mathcal{F}$ in the ideal process.

Chapter XVI
Multimedia Encryption and Watermarking in Wireless Environment

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ABSTRACT

In a wireless environment, multimedia transmission is often affected by the error rate; delaying; terminal's power or bandwidth; and so forth, which brings difficulties to multimedia content protection. In the past decade, wireless multimedia protection technologies have been attracting more and more researchers. Among them, wireless multimedia encryption and watermarking are two typical topics. Wireless multimedia encryption protects multimedia content's confidentiality in wireless networks, which emphasizes on improving the encryption efficiency and channel friendliness. Some means have been proposed, such as the format-independent encryption algorithms that are time efficient compared with traditional ciphers; the partial encryption algorithms that reduce the encrypted data volumes by leaving some information unchanged; the hardware-implemented algorithms that are more efficient than software based ones; the scalable encryption algorithms that are compliant with bandwidth changes; and the robust encryption algorithms that are compliant with error channels. Compared with wireless multimedia encryption, wireless multimedia watermarking is widely used in ownership protection, traitor tracing, content authentication, and so forth. To keep low cost, a mobile agent is used to partitioning some of the watermarking tasks. To counter transmission errors, some channel encoding methods are proposed to encode the watermark. To keep robust, some means are proposed to embed a watermark into media data of low bit rate. Based on both watermarking and encryption algorithms, some applications arise, such as secure multimedia sharing or secure multimedia distribution. In this chapter, the existing wireless multimedia encryption and watermarking algorithms are summarized according to the functionality and multimedia type; their performances are analyzed and compared; the related applications are presented; and some open issues are proposed.

INTRODUCTION

With the development of multimedia technology and network technology, multimedia data are used more and more widely in human's daily life, such as mp3 sharing, video conference, video telephone, video broadcasting, video-on-demand, p2p streaming, and so forth. For multimedia data may be in relation with privacy, profit, or copyright, multimedia content protection becomes necessary and urgent. It permits that only the authorized users could access and read the multimedia data, it can detect the modification of the multimedia data, it can prove the ownership of the multimedia data, it can even trace the illegal distribution of the multimedia data, and so forth.

During the past decades, some means have been proposed to protect multimedia data. Among them, multimedia encryption (Furht & Kirovski, 2006) and multimedia watermarking (Cox, Miller, & Bloom, 2002) are two typical ones. Multimedia encryption algorithms protect multimedia data's confidentiality by encoding or transforming multimedia data into unintelligible forms under the control of the key. Thus, only the authorized users who have the correct key can recover the multimedia data successfully. Till now, some multimedia encryption algorithms have been proposed, which focus on the security, time efficiency, and communication friendliness (Zeng, Zhuang, & Lan, 2004). Multimedia watermarking algorithms protect multimedia data's ownership by embedding ownership information into multimedia data under the control of the key. Thus, the authorized users can extract or detect the ownership information and authenticate it. Many watermarking algorithms (Barni & Bartolini, 2004) have been proposed during the last decade, which consider security, imperceptibility, robustness and capacity, and so forth.

Recently, mobile/wireless multimedia communication has become more and more popular, which benefits from the improvement of the capability of mobile terminals and the bandwidth of wireless channel. Compared with wired communication, wireless multimedia communication has some special properties (Salkintzis & Passas, 2005). Firstly, the bandwidth is still limited compared with wired channels. Secondly, there are many more transmission errors in wireless communication, such as channel error, loss, delay, jitter, and so forth, which are caused by path error, fading, noise or interference, and so forth. Thirdly, wireless or mobile terminals are often of limited memory. Fourthly, the terminals are often energy-constraint caused by the scale-limited battery. These properties push some requirements to multimedia encryption and watermarking algorithms.

To meet mobile/wireless multimedia content protection, some mobile digital rights management (DRM) systems (Kundur, Yu, & Lin, 2004) have been proposed, such as Nokia's Music Player, NEC VS-7810, Open Mobile Alliance (OMA), and so forth. In these systems, multimedia encryption and multimedia watermarking are two core technologies. Compared with wired environment, wireless multimedia encryption and watermarking should consider some extra requirements. For example, the algorithms should be lightweight in order to meet the constraint energy of the terminals. Additionally, the algorithms should be robust against transmission errors in some extent. Furthermore, the algorithms should be scalable to switch between wireless services and wired services.

During the past decade, some means have been proposed to make suitable wireless multimedia encryption and watermarking algorithms. These algorithms obtain the security, efficiency, and error robustness by considering the properties of wireless/mobile multimedia communication. In this chapter, they are classified into several types according to the functionalities, and their performances are analyzed and compared. Additionally, some open issues are presented.

The rest of the chapter is arranged as follows. In the next section, the requirements of wireless/mobile multimedia encryption and watermarking are presented respectively. The multimedia encryption algorithms are analyzed and compared in the third section, and the watermarking algorithms are analyzed and compared in the fourth section. In the fifth section, some research topics and applications based on the combination of watermarking and encryption are presented, followed by some

open issues in the sixth section. Finally, in the last section, some conclusions are drawn.

GENERAL REQUIREMENTS OF MULTIMEDIA CONTENT PROTECTION

Requirements of Multimedia Encryption

Multimedia data are often of high redundancy, large volumes, real time operations, and the compressed data are of certain format. These properties require that wireless multimedia encryption algorithms should satisfy some requirements (Furht & Kirovski, 2006), such as content security, time efficiency, format compliance, and so forth. All of them are presented in detail as follows.

Security. In multimedia encryption, the security refers to content security. It is composed of two aspects, that is, cryptographic security and perceptual security. The former one refers to the security against such cryptographic attacks as brute-force attack, ciphertext-only attack, known-plaintext attack, and so forth. The latter one refers to the intelligibility of the encrypted multimedia content. Generally, for multimedia encryption, an encryption algorithm is regarded as secure if the cost for breaking it is no smaller than the one paid for the multimedia content's authorization. For example, in broadcasting, the news may be of no value after an hour. Thus, if the attacker can not break the encryption algorithm during an hour, then the encryption algorithm may be regarded as secure in this application. Thus, according to this case, encrypting only significant parts of multimedia data may be reasonable if the cryptographic security and perceptual security are both confirmed, which will decrease the encrypted data volumes.

Efficiency. The efficiency refers to both time efficiency and energy-consumption efficiency. Since real-time transmission or access is often required by multimedia-related applications, multimedia encryption algorithms should be time efficient so that they do not delay the transmission or access operations. Generally, two kinds of method can be adopted to improve time efficiency, that is, the first one is to reduce the encrypted data volumes, and the second one is to adopt fast encryption algorithms. Additionally, to adapt the energy-constraint devices, such as mobile terminals, handset, handheld, and so forth, the lightweight encryption algorithms are preferred to decrease the energy-consumption.

Compression ratio. Multimedia data are often compressed in order to reduce the storage space or transmission bandwidth. In this case, multimedia encryption algorithms should not change the compression ratio.

Format compliance. In multimedia data, the format information, such as file header, frame header, file tail, and so forth will be used by the decoder to realize synchronization. Encrypting multimedia data except the format information will keep the encrypted data stream format-compliant. Thus, the encrypted data can be previewed directly. Additionally, the format information can be used to resynchronize the transmission process in error environment.

Communication compliance. In wireless or mobile environment, transmission errors often happened, such as, channel error, loss, delay, or jitter. The good multimedia encryption algorithms should not cause error propagation. Thus, the error conditions will also be considered when designing a wireless/mobile multimedia encryption algorithm.

Direct operation. If the encrypted multimedia data can be operated directly, the decryption-operation-encryption triples can be avoided, and the efficiency can also be improved. A typical example is to support direct bit rate conversion, that is, the encrypted data stream can be cut off directly in order to adapt the channel bandwidth. This property brings convenience to the applications in wireless or mobile environment.

Requirements of Multimedia Watermarking

For multimedia watermarking algorithms, some performances are required, such as security, robustness, transparency, oblivious, vindicability,

and efficiency (Cox et al., 2002). Here, only the ones related to wireless/mobile environment are emphasized.

Security. Similar to an encryption algorithm, the construction of a watermarking algorithm should consider the security against various attacks (Kutter, Volosphynovskiy, & Herrigel, 2000; Linnartz & Dijk, 1998; Petitcolas, Anderson, & Kuhn, 1999). According to the attacker's ability, the attacks can be classified into several types: attack under the condition of knowing nothing about the watermarking system, attack knowing some watermarked copies, attack knowing the embedding algorithm, and the attack knowing the watermark detector. Generally, some encryption operations are introduced to watermarking algorithms in order to keep secure.

Imperceptibility. Imperceptibility means that the watermarked media data have no difference with the original ones in perception. It is also named transparency or fidelity. This makes sure that the watermarked copy is still of high quality and suitable for practical applications.

Robustness. Multimedia data are often processed during transmission process, and some of the processing operations are acceptable. Thus, the watermark should still be detected after these operations. Generally, the robustness refers to the ability for the watermark to survive such operations including general signal processing operations (filtering, noising, A/D, D/A, re-sampling, recompression, etc.) and geometric attacks (rotation, scaling, shifting, transformation, etc.). For wireless/mobile multimedia, transmission errors should also be considered, such as loss, delay, jitter, and so forth.

Efficiency. Efficiency refers to both time efficiency and energy-consumption efficiency. The watermarking algorithm with high time efficiency is more suitable for real time applications, such as video-on-demand, broadcasting, per-per-view, and so forth. For some energy-limited devices, the lightweight watermarking algorithm is preferred, which costs less power and is more efficient in implementation.

Oblivious detection. Oblivious detection means that the detection process needs not the original copy. It is also named blind detection. On the contrary, non-blind detection means that the original copy is required by the detection process. In practical applications, especially in wireless/mobile environment, memory is limited, and thus blind or oblivious detection is preferred.

THE ENCRYPTION ALGORITHMS FOR WIRELESS MULTIMEDIA

Some encryption algorithms have been proposed with respect to image, audio, speech, or video in wireless environment. These algorithms adopt some means to meet wireless communication requirements. According to the functionality, the encryption algorithms are classified into four types: (1) format independent encryption, (2) format compliant encryption, (3) communication compliant encryption, and (4) direct-operation supported encryption. The first type supports the media data of arbitrary format, the second one combines the encryption operation with the compression process, the third one considers the transmission errors, and the fourth one supports some direct operations on the encrypted multimedia data. In the following content, they are introduced and analyzed in detail.

Format Independent Encryption

Format independent encryption algorithms regard multimedia data as binary data and encrypt multimedia data without considering of the file format. Traditional ciphers (Mollin, 2006), such as DES, IDEA, AES, RSA, and so forth, encrypt text or binary data directly without considering of the file format. These ciphers have been included in the protocols, IP security (IPsec) and secure socket layer (SSL), and the package CryptoAPI, and these protocols are also included in a multilayer security framework (Dutta, Das, Li, & Auley, 2004). The energy requirements of most of the encryption algorithms are analyzed in Potlapally, Raghunathan, and Jha (2003), some of which are suitable for wireless applications. However, for wireless multimedia, some means should be made to im-

prove the efficiency. One solution is to implement the algorithms in hardware, and another one is to design lightweight algorithms.

Hardware implementation. To improve the encryption algorithms' efficiency, hardware implementation is a suitable solution. The security processing architectures are proposed in Raghunathan, Ravi, Hattangady, and Quisquater (2003), which include an embedded processor, a cryptographic hardware accelerator, and a programmable security protocol engine. For the core encryption algorithms, some experiments are done to show their suitability. For example, hardware implementation of triple data encryption standard (3DES) is proposed in Hamalainen, Hannikainen, Hamalainen, and Saarinen (2001). The experiments show that 3DES implementations with small area and reasonable throughput can be realized even though 3DES turns out to be quite large and resource-demanding. It is suitable for some applications in wireless LAN (WLAN). Compared with such block cipher as 3DES, stream ciphers have some good properties, such as immunity to error propagation, increased flexibility, and greater efficiency. The Linear Feedback Shift Register (LFSR)-based stream ciphers are implemented in hardware (Goodman & Chandrakasan, 1998), which are shown ideally suited to low power wireless communications as they can be constructed from very simple and power-efficient hardware. Additionally, some wireless suitable stream ciphers, for example, wired equivalent privacy (WEP), improved wired equivalent privacy (IWEP), and Ron's cipher #4 (RC4) are implemented in hardware and tested in WLAN (Tikkanen, Hannikainen, Hamalainen, & Saarinen, 2000). Among them, IWEP is more suitable for hardware and of lower cost than RC4 although it is of lower security than RC4. Generally, hardware implementation improves the computing efficiency, but it also brings some problems, for example, the high cost to upgrade the algorithms.

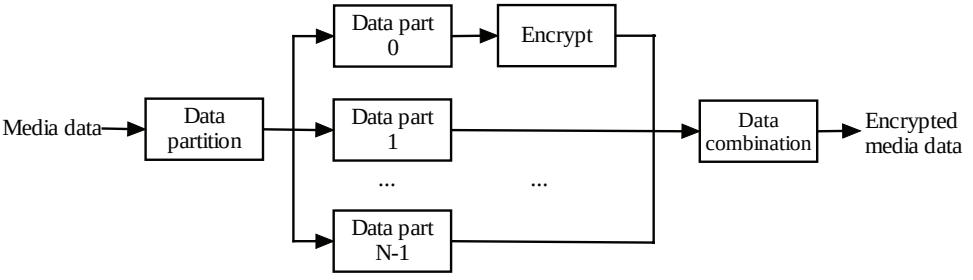
Lightweight encryption algorithms. Compared with hardware implementation, software implementation is cheaper and more flexible for upgrades. For wireless applications, some lightweight encryption algorithms have been proposed, such as WEP, IWEP, RC2, RC4, RC5, and so forth. Experiments are done in Ganz, Park, and Ganz (1998) to test the software efficiency of RC2, RC4, and RSA. It is shown that software implementation of these ciphers can meet the requirements of such wireless applications as multimedia e-mail, multimedia notes, telephone-quality audio, video conferencing or MPEG video interaction, and so forth. The disadvantage is that their performance is limited by the computer system configuration. Besides the experiments, some design guidelines (Ganz, Park, & Ganz, 1999) are proposed for real-time software encryption, which considers the WLAN throughput, quality of service (QoS) requirements, encryption throughput determined by computer configuration, and additional processing overhead incurred by other protocol layers.

Generally, the algorithms with higher security are often of higher computing complexity. In traditional applications, an encryption algorithm is evaluated in a one-or-nothing manner, for example, secure or insecure (Ong, Nahrstedt, & Yuan, 2003). In pervasive environments, it is insufficient, because the limited computing resources may limit the security requirement. Thus, a quality of protection (QoP) framework (Ong et al.) is proposed, which evaluates an encryption algorithm in an adaptive manner. That is, the security level can be tuned in order to meet some other performances suitable for wireless/mobile applications. For example, the QoP metadata may be <content type, interval of security, encryption algorithm, encryption key length, encryption block size>. By tuning these parameters in the metadata, the suitable performances can be obtained. This framework has the following properties: (1) it can tune the quality of protection, (2) it gets a balance between security and performance requirement, and (3) it is flexible and upgradable to support latest cryptographic standards. However, before using this scheme, some problems should be solved, for example, how and where to store or transmit the metadata.

Format Compliant Encryption

For multimedia data, partial encryption (Furht & Kirovski, 2006) can be used to reduce the en-

Figure 1. An example of partial encryption method



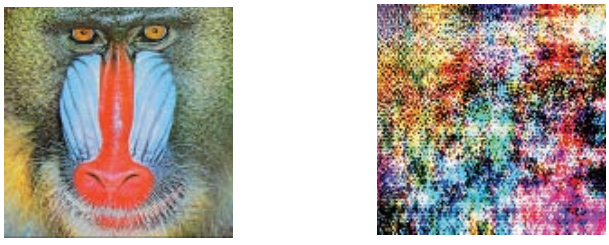
crypted data volumes, which keeps the file format unchanged. Additionally, the left format information can be used to synchronize the transmission process, especially in wireless/mobile environment where transmission errors often happen. The core of partial encryption is encrypting only the significant parameters in multimedia data while leaving other ones unchanged. Figure 1 gives an example for partial encryption, in which, media data are partitioned into N data parts, only the first data part is encrypted, while other parts are left unencrypted. The data part may be a block or region of the image, a frame of the video sequence, a bit-plane of the image pixels, a parameter of the compression codec, a segment of the compressed data stream, and so forth. The encrypted data part (Data part 0) and the other data parts are then combined together to generate the encrypted media data. The significance of the encrypted data part determines the security of the encryption scheme.

For multimedia data are often compressed before stored or transmitted, partial encryption often combines with compression codecs (Liu & Eskicioglu, 2003). That is, for different multimedia encoding codec, different partial encryption algorithm will be designed. During the past decade, some partial encryption algorithms have been proposed, which are classified and analyzed as follows according to the type of multimedia data and the codecs.

Partial audio encryption. Based on audio or speech codecs, some partial encryption algorithms have been proposed. For example, an algorithm based on G.729 (Servetti & Martin, 2002a, 2002b) is proposed to encrypt telephone-bandwidth speech. This algorithm partitions the code stream into two classes, for example, the most perceptually relevant one, and the other one. Among them, the former one is encrypted while the other one is left. It is reported that encrypting about 45% of the bitstream achieves content protection equivalent to full encryption. In another method (Sridharan, Dawson, & Goldburg, 1991), speech data are encrypted by encrypting only the parameters of Fast Fourier Transformation during speech encoding, and the correct parameters are used to recover the encrypted data in decryption. For MP3 (Gang, Akansu, Ramkumar, & Xie, 2001; Servetti, Testa, Carlos, & Martin, 2003) music, only the sensitive parameters of MP3 stream are encrypted, such as the bit allocation information, which saves much time or energy cost.

Partial image encryption. Some means are proposed to encrypt images partially or selectively. For raw images, only some of the most significant bit-planes are encrypted for secure transmission of image data in mobile environments (Podesser, Schmidt, & Uhl, 2002). Another image encryption algorithm (Scopigno & Belfiore, 2004) is proposed, which encrypts only the edge information in the image decomposition that produces three separate components: (1) edge location, (2) gray-tone or color inside the edges, and (3) residuum "smooth" image. For JPEG images, some significant bit-planes of discrete cosine transform (DCT)coefficients in JBIG are encrypted (Pfarrhofer & Uhl, 2005), and only DCT blocks are permuted and DCT coefficients' signs are encrypted in JPEG encoding

Figure 2. Experimental result of the image encryption algorithm



(a) Original image *(b) Encrypted image*

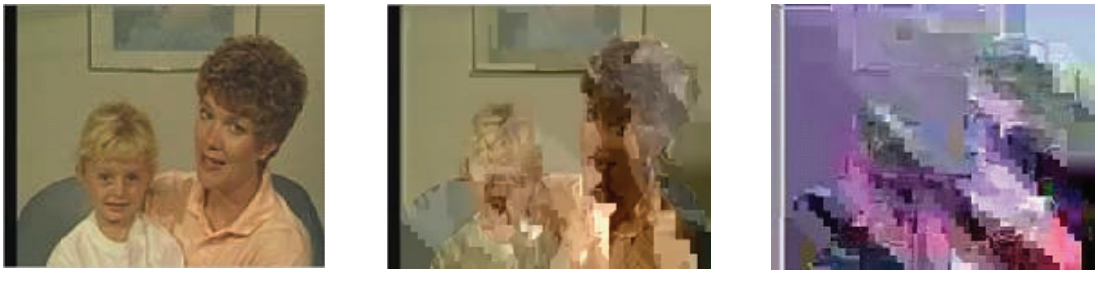
(Lian, Sun, & Wang, 2004a). These algorithms obtain high perceptual security and encryption efficiency. In JPEG2000 image encryption, only the significant streams in the encoded data stream are encrypted (Ando, Watanabe, & Kiya, 2001, 2002; Lian, Sun, & Zhang, 2004b; Norcen & Uhl, 2003; Pommer & Uhl, 2003), which is selected according to the scalability in space or frequency domain. These algorithms often keep secure in perception. Figure 2 gives the encryption result of the algorithm proposed in Lian et al., 2004b). As can be seen, the encrypted image is unintelligible. Additionally, in these algorithms, no more than 20% of the data stream is encrypted, which obtains high efficiency.

Partial video encryption. Compared with images or audios, videos are often of higher redundancy, which are compressed in order to save the transmission bandwidth. Among the video codecs, MPEG1/2, MPEG4, and H.264/AVC are more popular. Combined with them, some video encryption algorithms have been proposed, which saves time cost by encrypting the compressed video data selectively or partially.

In MPEG1/2 codec, the signs of DCT coefficients are encrypted with the video encryption algorithm (VEA) (Shi & Bhargava, 1998a), the signs of direct current coefficients (DCs) and motion vectors are encrypted with a secret key (Shi & Bhargava, 1998b), the base layer is encrypted while the enhancement layer is left unencrypted (Tosun & Feng, 2001a), the DCT coefficients are permuted (Lian, Wang, & Sun, 2004c; Tang, 1996), or the variable length coding (VLC) tables are modified by rearranging, random bit-flipping, or random bit-insertion (Wu & Kuo, 2000, 2001).

In MPEG4 codec, the Minimal Cost Encryption Scheme (Kim, Shin, & Shin, 2005) is proposed to encrypt only the first 8 bytes in the macroblocks (MBs) of a video object plane (VOP). It

Figure 3. Video encryption based on AVC codec



(a) Original *(b) Encrypted (Ahn et al., 2004)* *(c) Encrypted (Lian et al., 2005a)*

is implemented and proved suitable for wireless terminals. A format-compliant configurable encryption framework (Wen, Severa, Zeng, Luttrell, & Weiyin, 2002) is proposed for MPEG4 video encryption, which can be reconfigured for a given application scenario including wireless multimedia communication.

In H.264/AVC codec, the intra-prediction mode of each block is permuted with the control of the key (Ahn, Shim, Jeon, & Choi, 2004), which makes the video data degraded greatly. Some other algorithms (Lian, Liu, & Ren, 2005a; Lian, Liu, Ren, & Wang, 2006a) encrypt the DCT coefficients and motion vectors with sign encryption. For these algorithm encrypt both the texture information and motion information, they often obtain high security in human perception. Figure 3 shows the results of the algorithm proposed in Ahn et al. (2004) and the one proposed in Lian et al. (2005a). As can be seen, the video encrypted by the former algorithm is still intelligible, while the video encrypted by the latter algorithm is unintelligible. Thus, for high security, the latter encryption algorithm is preferred.

Communication Compliant Encryption

Multimedia data are often encrypted before being transmitted. In the encrypted data stream, transmission errors are often spread out due to encryption algorithms' ciphertext-sensitivity (Mollin, 2006). In wireless/mobile applications, some means should be taken to reduce the error propagation.

Constructing the encryption algorithms based on error correction code may be a solution. For example, the encryption algorithm based on forward error correction (FEC) code is proposed in Tosun & Feng, 2001b), which permutes the information-bits and complements a subset of the bits. The encryption algorithm can preserve the error robustness of the encrypted multimedia data, that is, the encrypted data stream can realize error correction itself. Additionally, the encryption algorithm is implemented very efficiently because of the simple encryption operations. Thus, it has some desirable properties suitable for wireless multimedia transmission. However, the disadvantage is also clear that it is not secure against known-plaintext attacks.

Another solution is to change the block length in data encryption. Generally, the block length is in close relation with the error propagation property. Taking stream cipher and block cipher for examples, the former one is of low error propagation, while the latter one is often of high error propagation. Generally, the bigger the block length is, the higher the error propagation is. Due to this case, a robust encryption scheme for secure image transmission over wireless channels is proposed in Nanjunda,

Figure 4. Robust video encryption based on segment

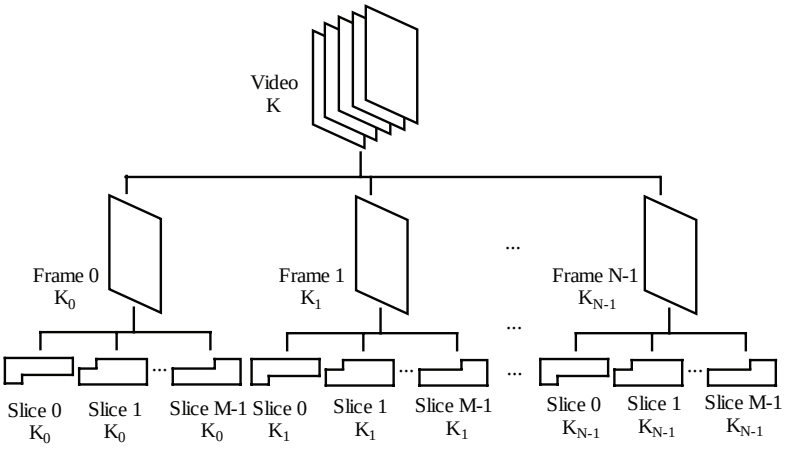
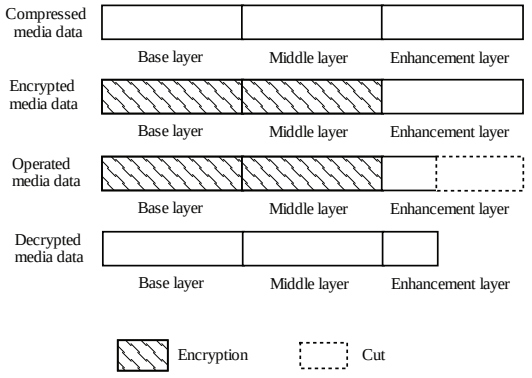


Figure 5. Scalable encryption scheme for MPEG2 video



Haleem, and Chandramouli (2005), which varies the block length according to the channel's error properties. This method obtains a trade-off between the security and error robustness. However, some problems should be solved before hand, for example, how to transmit the parameters of varying the block length, and how to determine the channel's error properties in advance.

Additionally, segment-based encryption algorithms are proposed to reduce the effect cause by transmission errors. By partitioning the plaintext into segments and encrypting each segment independently, the transmission errors can be limited in a segment. The only difficulty is to synchronize the segments. An example proposed in Lian, Liu, Ren, and Wang (2005b) is shown in Figure 4. It encrypts advanced video coding (AVC) videos according to the following steps: (1) partition the video data into N frames (each frame acts as a segment), (2) partition each frame into M macroblocks (each macroblock acts as a subsegment), and (3) encrypt each frame with different keys (K_0, K_1,…, K_{N-1}), and encrypt all the macroblocks in a frame with the same key. Thus, if a macroblock is lost, the other macroblocks can still be recovered correctly. If a frame is lost, the frame index can be used to synchronize the key, and recover other frames correctly. Thus, if the synchronization problem is solved, the segment based encryption will be a good solution in wireless/mobile applications.

Direct Operation Supported Encryption

To operate the encrypted multimedia data directly without decryption is challenging while cost efficient. Especially in wireless/mobile environment, no decryption and re-encryption operations are required, which saves much cost. Some solutions have been proposed to realize direct transcoding or bit rate conversion.

A secure transcoding scheme is proposed in Chang, Han, Li, and Smith (2004). In this scheme, the multimedia data are decomposed into multiple streams at the source, each stream is encrypted independently, and each stream is annotated with cleartext metadata. In transcoding, lower priority streams are dropped directly based on the cleartext metadata. The receiver can decrypt the remaining streams and recombine them into the transcoded output stream.

As progressive and scalable encoding becomes more and more popular, such as JPEG2000, MPEG4 FGS, SVC, and so forth, scalable encryption is focused, which supports direct bit rate conversion. The scalable encryption algorithm encrypts the progressive or scalable data streams, for example, base layer, middle layer, or enhance layer, one by one from the significant ones to the least significant ones. Thus, the bit rate can be changed by cutting the insignificant streams directly. For example, Tosun and Feng (2000) proposed the algorithm shown in

Figure 5, which encrypts only the base layer and middle layer in the three layers (base layer, middle layer, and enhancement layer) of an MPEG2 video stream. In this algorithm, the enhancement layer is left unencrypted, which can be cut off directly. Wee and Apostolopoulos (2001, 2003) and Zhu, Yuan, Wang, and Li (2005) proposed the algorithms for secure scalable streaming enabling transcoding without decryption. Generally, the stream is partitioned into segments according to the cipher's code length. To change the bit-rate, some segments at the end of the stream are cut off directly.

THE WATERMARKING ALGORITHMS FOR WIRELESS MULTIMEDIA

Watermarking algorithms (Barni & Bartolini, 2004; Cox et al., 2002) are generally composed of two parts, that is, watermark embedding and watermark extraction/detection. Generally, watermarking algorithms should be robust to some operations, such as recompression, A/D or D/A conversion, noise, filtering, and so forth and can survive such attacks as geometric attack, collusion attack, copy attack, and so forth. Similar to encryption algorithms, some watermarking algorithms may be of high security and robustness, but they are also of high time or energy cost. On the contrary, the watermarking algorithms with lost cost are often of low security or robustness. This contradiction becomes a problem in wireless/mobile environment when the limited energy or computing capability is provided. Experiments have been done to analyze the energy consumption, complexity and security level of multimedia watermarking on mobile handheld devices (Kejariwal, Nicolau, Dutt, & Gupta, 2005). And some conclusions are drawn: (1) the security level often contradicts with energy consumption, (2) watermark extraction/detection may be of higher cost than watermark embedding, and (3) image resolution affects the energy consumption. To conquer these problems, some proposals are presented, for example, introduce the tunable parameter to obtain trade-offs between security level, energy consumption, and other performances, or move some computationally expensive tasks to mobile proxies.

Mobile Agent Based Task Partitioning

Mobile agents use the proxies as agents that can connect to a range of heterogeneous mobile terminals. Using mobile agents to reduce the load of the server or terminals has been widely studied (Burnside et al., 2002; Rao, Chang, Chen, & Chen, 2001). If the mobile agent can implement watermark embedding or extraction/detection, then the terminals' computing load will be greatly reduced.

Figure 6. Watermarking tasks partitioning based on mobile agents

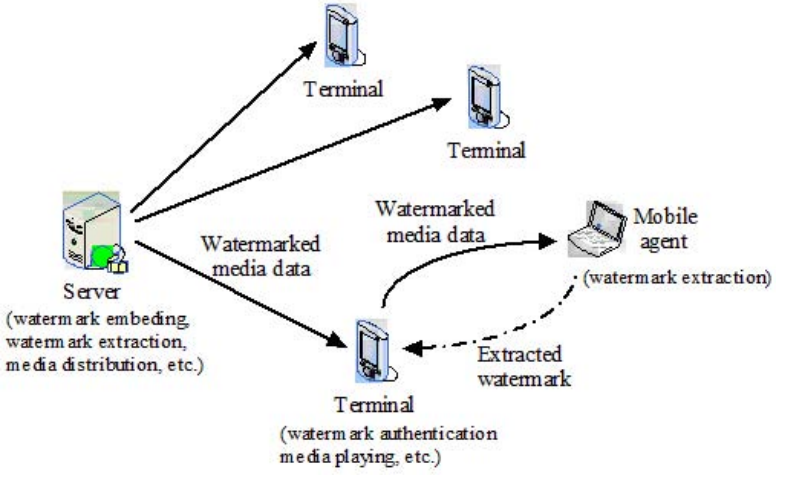
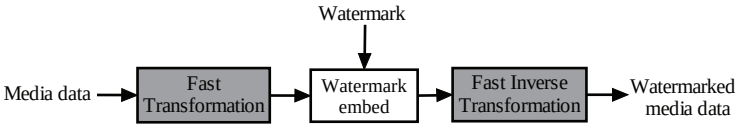
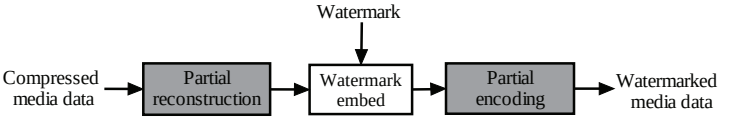


Figure 7. Architectures of some lightweight watermarking algorithms



(a) Fast transformation based watermarking embedding



(b) Watermarking embedding in compressed media data

The scheme proposed in Liu and Jiang (2005), as shown in Figure 6, uses mobile agent to replace terminals to realize watermark detection, which decreases the server and network's load during detecting watermarks. In another scheme (Kejariwal, Gupta, Nicolau, Dutt, & Gupta, 2004), the watermark embedding and detection tasks are both partitioned and moved to mobile proxies completely or partially. For example, to keep secure, only some tasks not sensitive to the security are moved out, such as image transformation, bit decomposition, plane alignment, and so forth. The partitioning schemes make watermarking applications more practical in mobile environment.

Lightweight Watermarking Algorithms

Using mobile agents to implement some watermarking related tasks can reduce the load of the server or terminals in some extent. However, frequent interaction between mobile agent and terminals are still costly. To reduce the cost of the server or terminals, improving the efficiency of watermarking embedding, or extraction/detection algorithms is a key problem. Considering that the watermark is often embedded into the transformation domain, some lightweight algorithms are proposed to implement transformation domain watermarking. Two typical ones are shown in Figure 7. The first one, as shown in Figure 7a, uses fast transformations to reduce the cost of converting media data into frequency domain. The second one, as shown in Figure 7b, embeds the watermark into the compressed media data according to the following steps: (1) reconstruct the coefficients partially from the compressed data stream, (2) embed the watermark into the selected coefficients, and (3) re-encode the watermarked coefficients. In the following content, some lightweight watermarking algorithms are introduced and analyzed.

A scalable watermarking algorithm is proposed to mark the audio data encoded with Advanced Audio Zip (AAZ) (Li, Sun, & Lian, 2005). In this algorithm, the watermark is embedded into the quantized modified discrete cosine transform (MDCT) coefficients in the core layer adaptively, and detected by computing the correlation between the spreading sequence and the bitstream. A speech watermarking scheme is proposed in Arora and Emmanuel (2003), which is designed based on the adaptive modulation of spread spectrum sequences and is robust against some removal or impairment attacks. The experiments in global system for mobile communications (GSM) cellular communications show that the algorithm is suitable for mobile applications.

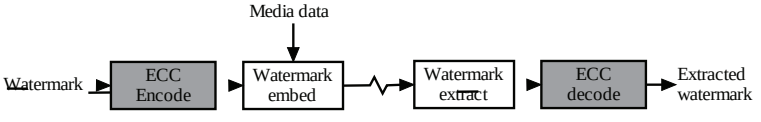
For images, an efficient steganography scheme (Pal, Saxena, & Muttoo, 2004) is proposed for resources constrained wireless networks. In this scheme, the coefficients in Hadamard transform-domain are manipulated to contain some hidden information. The Discrete Hadamard Transform can be implemented using fast algorithms, which makes the scheme computationally efficient and practical in mobile communications.

For videos, a spread spectrum watermarking algorithm (Petrescu, Mitrea, & Preteux, 2005) is proposed to protect low rate videos. In this algorithm, the DCT or wavelet coefficients of transformed video data are watermarked with spread spectrum sequences. Experiments are done for the videos varying from 64kbit/s to 256 kbit/s, and suitable transparency or robustness is obtained. Furthermore, a more efficient algorithm (Checcacci, Barni, Bartolini, & Basagni, 2000) is proposed to mark MPEG4 videos. In this algorithm, only the Luma macroblocks are watermarked by adjusting the coefficients' value in each coefficient pair. It is proved efficient in implementation and robust to transmission errors. Additionally, a more robust video watermarking algorithm (Alattar, Lin, & Celik, 2003) is proposed for low bit rate MPEG4 videos. In this algorithm, the watermark is composed of both the synchronization template and the watermark content combined with the template, and the watermark is embedded into the alternative current (AC) coefficients of the luminance plane of the VOPs. The template can survive geometric attacks, such as transcoding, cropping, scaling, rotation, noise, and so forth. Experiments on various videos are done, which show good performances for the video rate ranging from 128kbit/s to 768kbit/s.

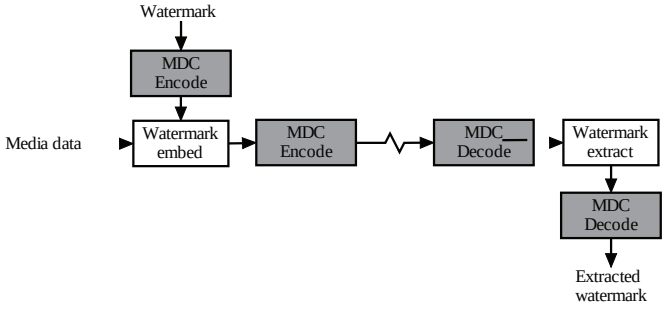
Communication Compliant Algorithms

In wireless/mobile communication, transmission errors often happen, which may reduce the watermark detection rate. Generally, several means may be adopted to improve the watermarking algorithm's robustness against transmission errors. The first one, as shown in Figure 8a, is applying

Figure 8. Architectures of some robust watermarking algorithms



(a) ECC based watermarking scheme



(b) MDC based watermarking scheme

error-correcting codes (ECC) to encode the watermark before embedding it into the multimedia data. For example, the watermark can be repeated for several times (Kundur, 2001), such codes as convolutional code, block code, or turbo code are used to encode the watermark (Ambroze et al., 2001), or the combination of watermark repetition and error-correcting code is used (Desset, Macq, & Vandendorpe, 2002). This kind of method improves the robustness by increasing the redundancy in the watermark. The second method, as shown in Figure 8b, is using multiple description code (MDC) to transmit the watermark or the watermarked multimedia data. For example, the watermark is encoded with MDC before being embedded (Hsia, Chang, & Liao, 2004), the watermarked media data are transmitted based on MDC (Chu, Hsin, Huang, Huang, & Pan, 2005; Pan, Hsin, Huang, & Huang, 2004), or both the watermark and the watermarked media data are encoded with MDC (Ashourian & Ho, 2003). This kind of method adopts the redundancy of multimedia data and is more suitable for the scenario of high error rate. Another method (Song, Kim, Lee, & Kim, 2002) partitions multimedia data into segments each of which fits for the packet in wireless transmission, and then embeds a watermark into each packet. Thus, it is robust to wireless packet error conditions including not only channel error but also delay and jitter.

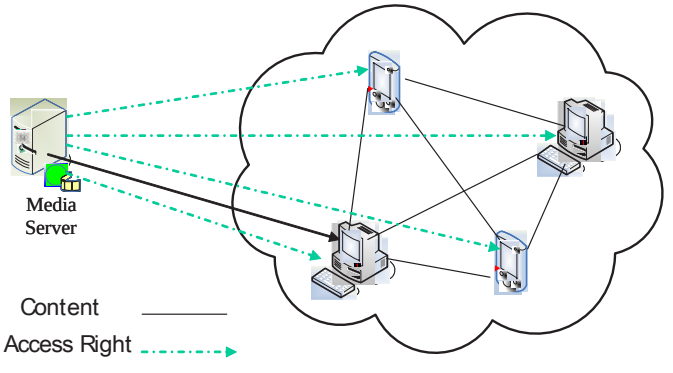
COMBINATION OF MULTIMEDIA ENCRYPTION AND MULTIMEDIA WATERMARKING

Multimedia encryption and watermarking realize different functionalities, for example, confidentiality protection and ownership protection, they can be combined together to provide stronger security. This is also required by some applications, such as secure multimedia sharing, secure multimedia distribution, or exchange between watermarking and encryption.

Secure Multimedia Sharing

Multimedia sharing is more and more popular with the development of network technology, especially when such a network as p2p is developed. Generally, in these applications, the ownership information is embedded into the multimedia data with watermarking technology, and then the watermarked multimedia data are encrypted and distributed. The ownership information can be extracted later to prove the ownership right, and the encryption process prevents unauthorized users from accessing the real content of the multimedia data. A typical example is the music sharing system, named Music2Share (Kalker, Epema, Hartel, Lagendijk, & Steen, 2004), as shown in Figure 9. In this system, the watermark representing ownership information is embedded into music files, and the

Figure 9. Architecture of a multimedia sharing system



watermarked files are encrypted then distributed over p2p networks. The customer can access the encrypted music files, while must apply for the right from the server before he can decrypt the files. The watermark extracted from the music file can prove the legality of the music.

Secure Multimedia Distribution

In secure multimedia distribution, multimedia data are transmitted from the server to customers in a secure way. In this case, the confidentiality can be protected, and the illegal distributor who redistributes his/her copy to other customers can be traced. Generally, both encryption and watermarking technology are used. Till now, three kinds of schemes have been proposed, which embed watermarks at the server side, in the router or at the client side, respectively. In the first kind of scheme, the customer information is embedded into multimedia data at the server side before multimedia encryption. This scheme is more suitable for unicast than for multicast or broadcast because it is difficult for the server to assign different copies to different customers simultaneously. In the second kind of scheme, the customer information is embedded by the routers in lower level (Brown, Perkins, & Crowcroft, 1999), which distributes the server's loading to the routers. This scheme reduces the server's loading, but also changes the network protocols. In the third kind of scheme, the customer information is embedded at the customer side (Bloom, 2003). This scheme is time efficient, but the security is a problem because of the isolation between decryption and watermarking. Some means (Anderson & Manifavas, 1997; Kundur & Karthik, 2004; Lian, Liu, Ren, & Wang, 2006b) have been proposed to improve the security, which combine decryption with watermark embedding. These combined methods improve the system's security at the same time of keeping low cost.

Commutative Watermarking and Encryption

Generally, watermarking operation and encryption operation are separate. That is, the encrypted multimedia data should be decrypted before being watermarked. In some applications, if the operation triple decryption-watermarking-encryption can be avoided, the operation cost will be reduced greatly. In this case, the encrypted multimedia data can be watermarked directly without decryption, and the watermark can be extracted directly from the encrypted or decrypted multimedia data. This kind of watermarking-encryption pair is named commutative watermarking and encryption (CWE). A practical scheme is proposed in Lian, Liu, Ren, and Wang (2006c), which is based on partial encryption. In this scheme, multimedia data are partitioned into two parts, that is, the perception significant part and the robust part, among which, the perception significant part is encrypted, while the robust part is watermarked. Thus, the encryption and watermarking are independent of each other, and they support the commutative operations.

OPEN ISSUES

Contradiction Between Format Independence and Format Compliance

To keep low cost, partial encryption scheme is used to encrypt multimedia data, which keeps format compliant. Thus, for different multimedia data or different codec, the encryption algorithms are often different. If various multimedia data are included in an application, then various encryption algorithms should be used, and some extra information is required to tell which encryption algorithm has been used. Compared with format compliant encryption, format independent encryption regards multimedia data as binary data and is easy to support various data. Thus, for the applications with versatile data, format independent encryption is more suitable. For example, in such DRM systems as internet streaming media alliance (ISMA), advanced access content system (AACS), or open mobile alliance (OMA) (Kundur et al., 2004), the algorithms, advanced encryption standard (AES) and data encryption standard (DES), are recommended to encrypt multimedia data not considering the file

format. Thus, for practical applications, the trade-off between computational cost and convenience is to be made, which determines which kind of algorithm should be used.

Standardization of Watermarking Algorithms

Compared with encryption algorithms that have been standardized to some extent, watermarking algorithms are still in study. For the diversity of multimedia content, the difficulty in multimedia understanding and the variety of applications, it is difficult to standardize multimedia watermarking algorithms. Generally, they have different performances in security, efficiency, robustness, capacity, and so forth. Using which watermarking algorithm depends on the performances required by the applications. Defining suitable watermarking algorithms will provide more convenience to wireless/mobile applications.

Fingerprint Algorithms Against Collusion Attacks

In secure multimedia distribution, collusion attack (Zhao, Wang, & Liu, 2005) threatens the system. That is, different customers combine their copies together through averaging, substitution, and so forth, which produces a copy without any customer information. To counter this attack, some fingerprint encoding methods (Boneh & James, 1998; Wu, Trappe, Wang, & Liu, 2004) have been proposed. These methods generate different fingerprint codes for different customers, and the colluded copy can still tell one or more of the colluders. However, there is still a trade-off between the watermark capacity and the supported customers, and some new attacks are still not predicted, such as the linear combination collusion attack (LCCA) attack (Wu, 2005). Thus, better fingerprint encoding methods with good efficiency are expected.

Key Management in Mobile Applications

Multimedia encryption and watermarking can both be controlled by the keys; key management needs to be investigated. For example, whether the encryption key should be independent of the watermarking key, and how to assign different decryption keys to different customers in multimedia distribution? Additionally, for multicast or p2p networks, key generation and distribution (Cherukuri, 2004; Eskicioglu, 2002) are important topics not only in fixed networks but also in mobile environments.

CONCLUSION

In this chapter, mobile/wireless multimedia encryption and watermarking algorithms are introduced and analyzed, including the general requirements, various multimedia encryption algorithms, some watermarking algorithms, the combination between encryption and watermarking, and some open issues. Among them, the multimedia encryption algorithms are classified and analyzed according to the functionalities, and the watermarking algorithms with low cost are emphasized. The combination between encryption and watermarking brings up some new research topics, for example, fingerprint or commutative watermarking and encryption. And some open issues are also presented, including the contradiction between format compliance and format independence, the standardization of watermarking algorithms, the fingerprint algorithms resisting collusion attacks, and the key management in mobile applications.

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KEY TERMS

Commutative Watermarking and Encryption: Commutative watermarking and encryption is the watermarking-encryption pair that supports the exchange between the encryption algorithm and the watermarking algorithm. Thus, the media data can either be watermarked followed by encryption or be encrypted followed by watermarking.

Digital Watermarking: Digital watermarking is the technology to embed information into the original data by modifying parts of the data. The produced data are still usable, from which the information can be detected or extracted.

Format Compliant Encryption: Format compliant encryption is the multimedia encryption method that keeps the format information unchanged. In this method, the encrypted media data can be decoded or browsed by a general decoder or player.

Joint Fingerprint Embedding and Decryption: Joint fingerprint embedding and decryption is the technology to implement fingerprint embedding and data decryption at the same time. The input is the encrypted media copy, while the output is the decrypted media copy with a unique fingerprint, for example, the customer ID.

Partial Encryption: Partial encryption is the encryption method that encrypts only parts of the original data while leaving the other parts unchanged. In this method, traditional ciphers can be used to encrypt the selected parts.

Robust Watermarking: Robust watermarking is the watermarking algorithm that can survive not only such general operations such as compression, adding noise, filtering, A/D or D/A conversion, and so forth, but also such geometric attacks such as rotation, scaling translation, shearing, and so forth. It is often used in ownership protection.

Scalable Encryption: Scalable encryption is the multimedia encryption method that keeps the scalability of the progressive or scalable media data. The scalable media data can be produced by such codecs as JPEG2000, MPEG4, scalable video coding (SVC), and so on.

Chapter XVII
System-on-Chip Design of the Whirlpool Hash Function

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ABSTRACT

In this chapter, a system-on-chip design of the newest powerful standard in the hash families, named Whirlpool, is presented. With more details an architecture and two very large-scale integration (VLSI) implementations are presented. The first implementation is suitable for high speed applications while the second one is suitable for applications with constrained silicon area resources. The architecture permits a wide variety of implementation tradeoffs. Different implementations have been introduced and each specific application can choose the appropriate speed-area, trade-off implementation. The implementations are examined and compared in the security level and in the performance by using hardware terms. Whirlpool with RIPEMD, SHA-1, and SHA-2 hash functions are adopted by the International Organization for Standardization (ISO/IEC, 2003) 10118-3 standard. The Whirlpool implementations allow fast execution and effective substitution of any previous hash families' implementations in any cryptography application.

INTRODUCTION

Nowadays many financial and other electronic transactions are grown exponentially and they play an important role in our life. All these transactions have integrated data authentication processes. In addition many applications like the public key infrastructure (PKI) (Adams & Farrell, 1999; National Institute of Standards and Technology [NIST, 2005=http://csrc.nist.gov/publications/nistpubs/800-77/sp800-77pdf]) and many mobile communications include authentication services. All the aforementioned applications have integrated an authentication module including a hash function embedded in the system's implementation.

A hash function is a function that maps an input of arbitrary length into a fixed number of output bits, the hash value.

One of the most widely used hash function is RIPEMD (Dobbertin, Bosselaers, & Preneel, 1996). These are two different RIPEMD versions the RIPEMD-128 and the RIPEMD-160, with similar design philosophy but different word length of the produced message digest (128- and 160-bit,

respectively). In August 2002, NIST announced the updated Federal Information Processing Standard (FIPS 180-2), which has introduced another three new hash functions referred to as SHA-2 (256, 384, 512). In addition, the new European schemes for signatures, integrity, and encryption (NESSIE) (2004), was responsible to introduce a hash function with high security level. In February 2003, it was announced that the hash function included in the NESSIE portfolio is Whirlpool (Barreto & Rijmen, 2003). Finally, the most known hash function is the secure hash algorithm-1 (SHA-1) (NIST, 1995=http://itl.nist.gov/fipspub/fip180-1.htm). However, some security problems have been raised as it has already (see Wang, Yin, & Yu, 2005) shown. This collision of SHA-1 can be found with complexity less than 2^{69} hash operations. This is the first attack on the full 80-step SHA-1 with complexity less than the 2^{80} theoretical bound. A collision in SHA-1 would cast doubt over the future viability of any system that relies on SHA-1. The result will cause a significant confusion and it will create reengineering of many systems, and incompatibility between new systems and old. In addition, the National Security Agency (NSA) did not disclose the SHA-2 design criteria and also its design philosophy is similar to the design of SHA-1 function. So, the attack against SHA-1 probably will have affected to the SHA-2 function. Also, this issue stands for RIPEMD hash families. On the other hand, the internal structure of Whirlpool is different from the structure of all the aforementioned hash functions. So, Whirlpool function does not suffer for that kind of problems and makes it a very good choice for electronics applications.

All the afore-mentioned hash functions are adopted by the International Organization for Standardization (ISO, 2003) 10118-3 standard.

In this chapter, an architecture and two VLSI implementations of the new hash function, Whirlpool, are proposed. The first implementation is suitable for high speed applications while the second one is suitable for applications with constrained silicon area resources.

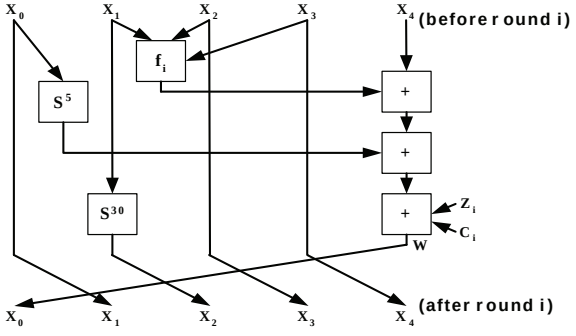
The architecture and the implementations presented here were the first in scientific literature (Kitsos & Koufopavlou, 2004). Until then, two hardware architectures have been also presented. The first one (McLoone & McCanny, 2002) is a high speed hardware architecture and the second one (Pramstaller, Rechberger, & Rijmen, 2006) is a compact field-programmable gate array **(**FPGA) architecture and implementation of Whirlpool. Both architectures are efficient for specific applications; analytical comparisons with the proposed implementations will be given in the rest of this chapter. In addition, comparisons with other hash families' implementations (Ahmad & Shoba Das, 2005; Deepakumara, Heys, & Venkatesam, 2001; Dominikus, 2002; Grembowski et al., 2002; McLoone, McIvor, & Savage, 2005; Sklavos & Koufopavlou, 2003, 2005; Yiakoumis, Papadonikolakis, Michail, Kakarountas, & Goutis, 2005); are provided. From the comparison results it is proven that the proposed implementation performs better and composes an effective substitution of any previous hash families' such as MD5, RIPEMD-160, SHA-1, SHA-2, and so forth, in all the cases.

The organization of the chapter is the following: In the second section, fundamental for hash functions families, is presented. So, the (ISO/IEC) 10118-3 standard first is briefly described and secondly the Whirlpool hash function specifications are defined. In the third section, the proposed architecture and VLSI implementations are presented. Implementation results and discussion (comparison with other works) are reported in the fourth section. Finally, the fifth section concludes this chapter.

FUNDAMENTALS FOR HASH FUNCTIONS

In this section a brief description of the ISO/IEC 10118-3 standard is presented. This standard specifies dedicated hash functions. The hash functions are based on the iterative use of a round-function. Seven distinct round functions are specified, giving rise to distinct dedicated hash-functions. Six of them are briefly described and at last, Whirlpool is described in details.

Figure 1. The SHA-1 round function



Dedicated Hash Functions

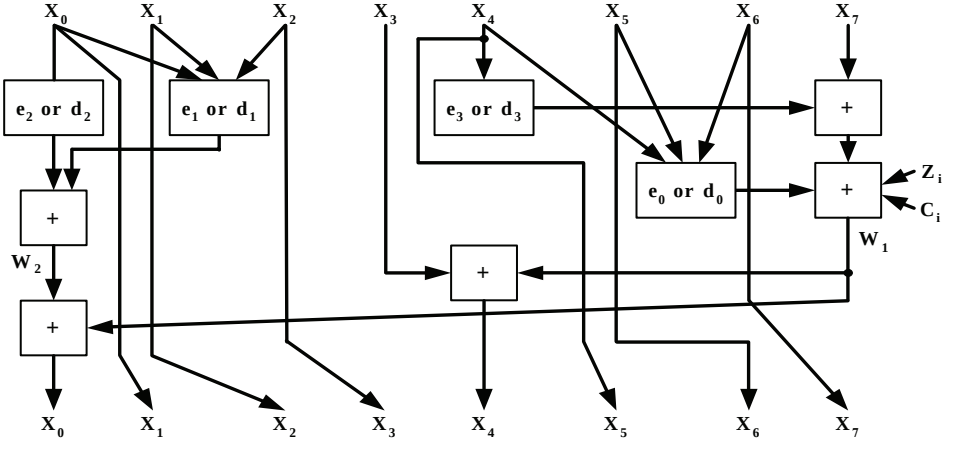
In each SHA-1 round, a hash operation is performed that takes as inputs five 32-bit variables, and two extra 32-bit words. The first one is the message schedule, Z_i, which is provided by the padding unit, and the other word is a constant, C_i, predefined by the standard. Figure 1 shows the diagram of the SHA-1 round function.

The sequence of functions f_0, f_1, ., f_{79} is used in this round-function, where each function f_i, $0 \leq i \leq 79$ takes three words X_1, X_2 and X_3 as input and produces a single word as output. The operations S^5 and S^{30} means circular left shift by 5-bit and 30-bit positions respectively.

The algorithm for generation of message digest is identical for SHA-256 and SHA-512 and only the constants (C_i) and functions, e_i and d_i that they have been used differs (the functions e_i used by SHA-256 and functions d_i used by SHA-512), and hence, SHA-256 and SHA-512 are discussed simultaneously. The diagram of the SHA-256 and SHA-512 round function is depicted in Figure 2.

When a message of any length $<2^{64}$ bits, for SHA-256, or $<2^{128}$ bits, for SHA-512 is input, the hash functions SHA-256 and SHA-512 compute the message digest. The message digest generated by SHA-256 and SHA-512 are 256 and 512 bits long, respectively. The procedure consists of two stages, namely, preprocessing and hash computation. In

Figure 2. The SHA-256 and SHA-512 round function



the preprocessing stage, the message is padded, parsed into *m*-bit blocks and initialization values are been set in order to hash computation. A message scheduler divides the *m*-bit block into 16 words and prepares a message schedule by passing one word at a time. A series of hash values are generated iteratively from functions, constants, and word operations and the final hash value is the message digest. SHA-256 requires 64 transformation steps (round-functions) while SHA-512 requires 80 round function transformations.

SHA-384 uses exactly the same round function as SHA-512 and requires 80 round function transformations. Only the initialization values are different. The 384-bit message digest is obtained by truncating the SHA-512-based hash output to its left-most 384-bit.

RIPEMD-160 and RIPEMD-128 replaces the previous published version of RIPEMD and overcomes the security problems that they have raised (see Dobbertin, 1997). The main design principle of both hash functions is to maximize the confidence gained by RIPEMD, but with as few changes as possible to the original structure. The produced message digest, ranges in length from 128- to 160-bit, depending on the selected hash function each time. These hash functions enable the determination of a message's integrity. Any change to the message will, with a very high probability, result in a different produced message digest.

The round-function of RIPEMD-160 is described in terms of operations on 32-bit words. A sequence of functions g_0, g_1, ., g_{79} is used in this round-function, where each function g_i, $0 \leq i \leq 79$, takes three words X_1, X_2 and X_3 as input and produces a single word as output. Two sequences of constant words C_0, C_1, ., C_{79} and C'_0, C'_1, ., C'_{79} are used in this round-function. Besides, two sequences of 80 shift-values are used in this round-function, where each shift-value is between 5 and 15. The diagram of the RIPEMD-160 round function is illustrated in Figure 3.

As Figure 4 shows, the round-function of RIPEMD-128 is described in terms of operations on 32-bit words. A sequence of functions g_0, g_1, ., g_{63} is used in this round-function, where each function g_i, $0 \leq i \leq 63$, takes three words X_1, X_2 and X_3 as input and produces a single word as output. Two sequences of constant words C_0, C_1, ., C_{63} and C'_0, C'_1, ., C'_{63} are used in this round-function. Two sequences of 64 shift-values are also used in this round-function, where each shift-value is between 5 and 15.

Whirlpool Hash Function Specifications

Whirlpool is a one-way, collision resistant 512-bit hash function operating on messages less than 2^{256} bits in length. It consists of the iterated application

Figure 3. The RIPEMD-160 round function

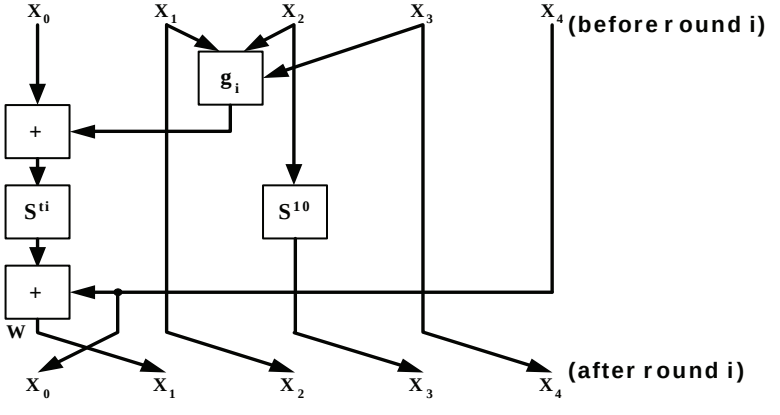
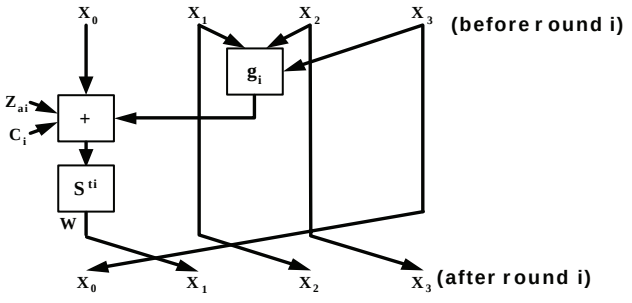


Figure 4. The RIPEMD-128 round function



of a compression function, based on an underlying dedicated 512-bit block cipher that uses a 512-bit key. The Whirlpool is a Merkle hash function (Menezes, Van Oorschot, & Vastone, 1997) based on a 512-bit block cipher, W, using a chained 512-bit key state, both derived from the input data. The round function, of the W, is operating in the Miyaguchi-Preneel mode (Menezes et al.) as shown in Figure 5.

As Figure 5 shows, a 512-bit data block, m_i, with a 512-bit key, h_{i-1}, is used for the operation of W block cipher. The output of the block cipher with the original input data block and also with the input key are all together XORed in order to produce the hash value, h_i. This hash value is used as a key in the next input data block.

In the rest of this chapter, the round function of the block cipher, W, is defined. The block diagram of the W block cipher basic round is depicted in Figure 6. The round function, $\rho[k]$, is based on combined operations from three algebraic functions. These functions are the non-linear layer γ, the cyclical permutation π, and the linear diffusion layer θ. So, the round function is the composite mapping $\rho[k]$, parameterized by the key matrix k, and given by the following equation.

$$\rho[k] \equiv \sigma[k] \circ \theta \circ \pi \circ \gamma \qquad (1)$$

Symbol "$\circ$" denotes the sequential operation of each algebraic function where the right function is executed first.

The key addition $\sigma[k]$, consists of the bitwise addition (XOR) of a key matrix k such as:

$$\sigma[k](a) = b \Leftrightarrow b_{ij} = a_{ij} \oplus k_{ij}, 0 \le i, j \le 7 \qquad (2)$$

This mapping is also used to introduce round constants in the key schedule. The input data (hash state) is internally viewed as a 8x8 matrix over $GF(2^8)$. Therefore, 512-bit data string must be mapped to and from this matrix format. This can be done by function μ such as:

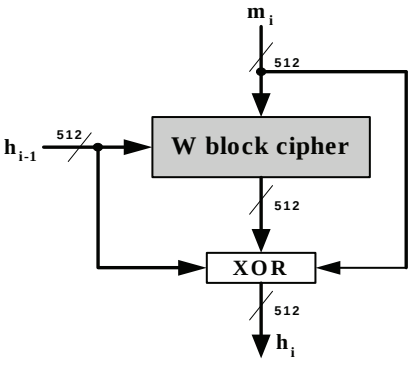
$$\mu(a) = b \Leftrightarrow b_{ij} = a_{8i+j}, 0 \le i, j \le 7 \qquad (3)$$

The first transformation of the hash state is through the non-linear layer γ, which consists of the parallel application of a non-linear substitution *S-Box* to all bytes of the argument individually. After, the hash state is passed through the permutation π that cyclical shifts each column of its argument independently, so that column j is shifted downwards by j positions. The final transformation is the linear diffusion layer θ, which the hash state is multiplied with a generator matrix. The effect of θ is the mix of the bytes in each state row.

So, the dedicated 512-bit block cipher $W[K]$, parameterized by the 512-bit cipher key K, is defined as:

$$W[K] = \left(O_1^{r=R} \rho[K^r]\right) \circ \sigma[K^0] \qquad (4)$$

Figure 5. Whirlpool hash function



where, the round keys $K^0,\ldots, K^R$ are derived from K by the key schedule. The default number of rounds is R=10. The key schedule expands the 512-bit cipher key K onto a sequence of round keys $K^0,\ldots, K^R$ as:

$$K^0 = K$$
$$K^r = \rho[c^r](K^{r-1}), r > 0 \qquad (5)$$

The round constant for the *r*-th round, *r*>0, is a matrix c^r defined by substitution box (S-Box) as:

$$c_{oj}^r \equiv S[8(r-1)+j], 0 \le j \le 7,$$
$$c_{ij}^r \equiv 0, \qquad 1 \le i \le 7, 0 \le j \le 7 \qquad (6)$$

So, the Whirlpool iterates the Miyaguachi-Preneel hashing scheme over the *t* padded blocks m_i, $1 \le i \le t$, using the dedicated 512-bit block cipher W:

$$n_i = \mu(m_i),$$
$$H_0 = \mu(IV),$$
$$H_i = W[H_{i-1}](n_i) \oplus H_{i-1} \oplus n_i, 1 \le i \le t \qquad (7)$$

where, *IV* (the Initialization Vector) is a string of 512 0-bits.

As Equations 4 and 5 show the internal block cipher W, comprises of a data randomizing part and a key schedule part. These parts consist of the same round function.

Before being subjected to the hashing operation, a message *M* of bit length $L<2^{256}$ is padded with a 1-bit, then as few 0-bits as necessary to obtain a bit string whose length is an odd multiple of 256,

Figure 6. Block diagram of the W basic round with algebraic functions transformations

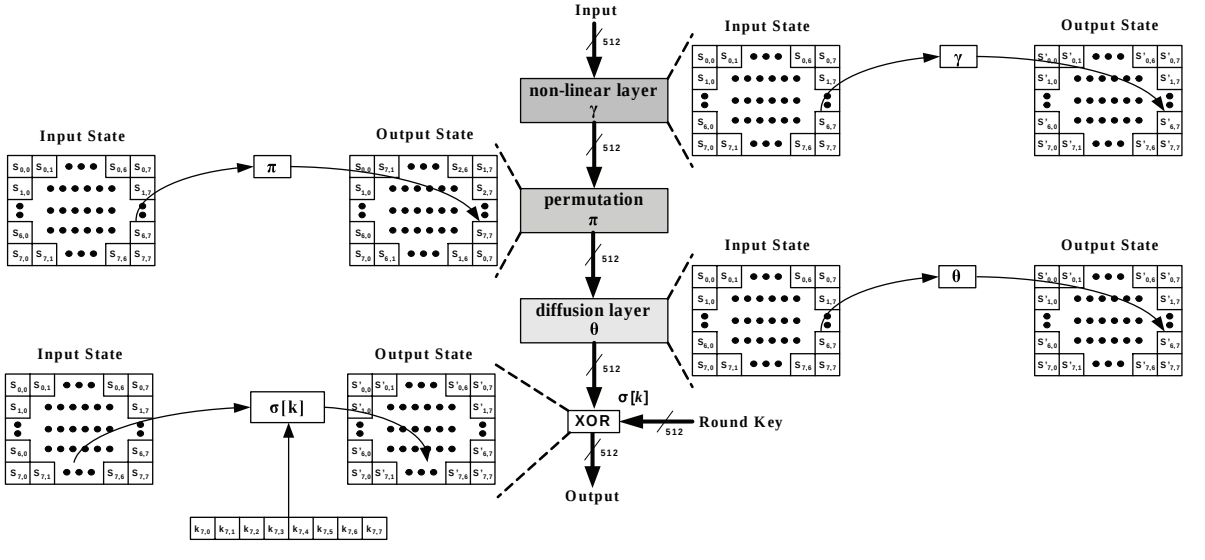
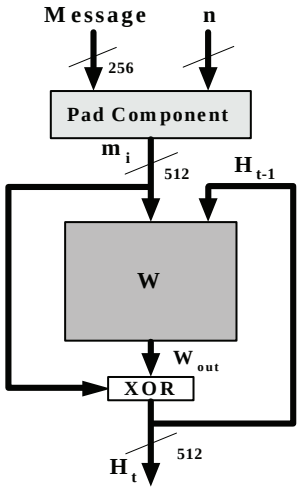


Figure 7. Whirlpool hash function architecture



and finally with the 256-bit right-justified binary representation of L, resulting in the padded message m, partitioned in t blocks $m_1, m_2, \ldots, m_t$.

WHIRLPOOL ARCHITECTURES AND VLSI IMPLEMENTATIONS

In this paragraph the proposed architecture and implementations are explained in detail of the hash function Whirlpool. A general diagram of the architecture that performs the Whirlpool hash function is shown in Figure 7. The *Pad Component* pads the input data and converts them to n-bit padded message. In the proposed architecture an interface with 256-bit input for *Message* is considered. The input *n*, specifies the total length of the message. The padded message is partitioned into a sequence of t 512-bit blocks $m_1, m_2, \ldots, m_t$. This sequence is then used in order to generate a new sequence of 512-bit string, $H_1, H_2, \ldots, H_t$ in the following way. m_i is processed with H_{i-1} as key, and the resulting string is XORed with m_i in order to produce the H_i. H_0 is a string of 512 *0*-bits and H_t is the hash value.

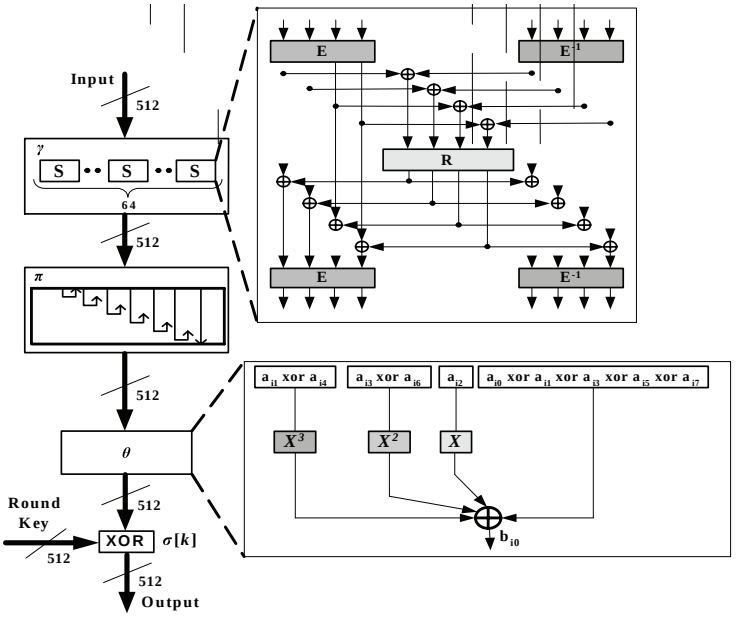
The block cipher W, is mainly consists of the round function ρ. The implementation of the round function ρ is illustrated in Figure 8.

The non-linear layer γ, is composed of 64 substitution tables (S-Boxes). The internal structure of the S-Box is shown in Figure 8. It consists of five 4-bit mini boxes E, E^{-1}, and R. These mini boxes can be implemented either by using look-ip-tables (LUTs) or Boolean expressions. Next, the cyclical permutation π, is implemented by using combinational shifters. These shifters are cyclically shift (in downwards) each matrix column by a fixed number (equal to j), in one clock cycle. The linear diffusion layer θ, is a matrix multiplication between the hash state and a generator matrix. In Barreto and Rijmen (2003) an efficient method is provided in order to implement the matrix multiplication. However, in this chapter an alternative way is proposed which

Equation 8.

$$b_{i0} = a_{i0} \oplus a_{i1} \oplus a_{i3} \oplus a_{i5} \oplus a_{i7} \oplus X[a_{i2}] \oplus X^2[a_{i3} \oplus a_{i6}] \oplus X^3[a_{i1} \oplus a_{i4}]$$
$$b_{i1} = a_{i0} \oplus a_{i1} \oplus a_{i2} \oplus a_{i4} \oplus a_{i6} \oplus X[a_{i3}] \oplus X^2[a_{i4} \oplus a_{i7}] \oplus X^3[a_{i2} \oplus a_{i5}]$$
$$b_{i2} = a_{i1} \oplus a_{i2} \oplus a_{i3} \oplus a_{i5} \oplus a_{i7} \oplus X[a_{i4}] \oplus X^2[a_{i5} \oplus a_{i0}] \oplus X^3[a_{i3} \oplus a_{i6}]$$
$$b_{i3} = a_{i0} \oplus a_{i2} \oplus a_{i3} \oplus a_{i4} \oplus a_{i6} \oplus X[a_{i5}] \oplus X^2[a_{i6} \oplus a_{i1}] \oplus X^3[a_{i4} \oplus a_{i7}]$$
$$b_{i4} = a_{i1} \oplus a_{i3} \oplus a_{i4} \oplus a_{i5} \oplus a_{i7} \oplus X[a_{i6}] \oplus X^2[a_{i7} \oplus a_{i2}] \oplus X^3[a_{i5} \oplus a_{i0}]$$
$$b_{i5} = a_{i0} \oplus a_{i2} \oplus a_{i4} \oplus a_{i5} \oplus a_{i6} \oplus X[a_{i7}] \oplus X^2[a_{i0} \oplus a_{i3}] \oplus X^3[a_{i6} \oplus a_{i1}]$$
$$b_{i6} = a_{i1} \oplus a_{i3} \oplus a_{i5} \oplus a_{i6} \oplus a_{i7} \oplus X[a_{i0}] \oplus X^2[a_{i1} \oplus a_{i4}] \oplus X^3[a_{i7} \oplus a_{i2}]$$
$$b_{i7} = a_{i0} \oplus a_{i2} \oplus a_{i4} \oplus a_{i6} \oplus a_{i7} \oplus X[a_{i1}] \oplus X^2[a_{i2} \oplus a_{i5}] \oplus X^3[a_{i0} \oplus a_{i3}]$$

Figure 8. Implementation of the round function ρ



is suitable for hardware implementation. The transformation expressions of the diffusion layer are given next. (See Equation 8.)

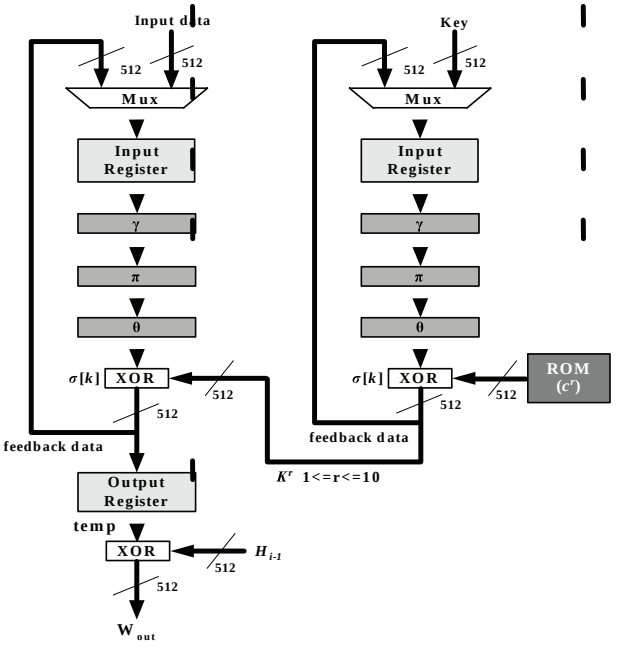
Bytes b_{i0}, b_{i1}, b_{i2},… , b_{i7} represent the eight bytes of the *i* row of the output of the layer θ hash state. Table *X* implements the multiplication by the polynomial $g(x)=x$ modulo $(x^8+x^4+x^3+x^2+1)$ in $GF(2^8)$. Table X^2 is defined as $X^2 \equiv X \circ X$ and X^3 as $X^3 \equiv X \circ X \circ X$. In Figure 8, the implementation of the output byte b_{i0} is depicted in details. The other bytes are implemented in a similar way. The key addition ($\sigma[k]$) consists of eight 2-input XOR gates for any byte of the hash state. Every bit of the round key is XORed with the appropriate bit of the hash state.

The first implementation is depicted in Figure 9. This implementation has two similar parallel data paths, the *data randomizing* and the *key schedule*. The implementation details of the non-linear layer γ, the cyclical permutation π, and the linear diffusion layer θ are shown in Figure 8. The input block m_i is set to the *Input data* simultaneously with the *initial vector* (*IV*) to the *Key*. In the key schedule data path, the output data of the θ layer is bitwise XORed with the c^r constant. A round key is produced, on the fly, in one clock cycle. Each produced round key is used in the next clock cycle (through the multiplexer) for the production of the next round key. In the data randomizing data path, the hash state of the θ layer is bitwise XORed with the appropriate round key. After, the intermediate feedback data are used as input to the next round (through the multiplexer). After 10 execution rounds the *Output Register* latches the *temp* value. This is bitwise XORed with the H_{i-1} value in order to compute the W_{out}.

In a clock cycle, one execution round is executed and, simultaneously, the appropriate round key is calculated. The system needs 10 clock cycles per block. If another block m_{i+1} is required to be transformed, the previous process is repeated (by using as cipher key the H_i value). So, for *t* blocks the execution time is *10*t* clock cycles.

The second implementation of the W block cipher architecture is shown in Figure 10. This implementation is suitable for applications with constrained silicon area resources. The appropriate key schedule part is integrated with the data

Figure 9. The implementation of the W block cipher suitable for high speed applications



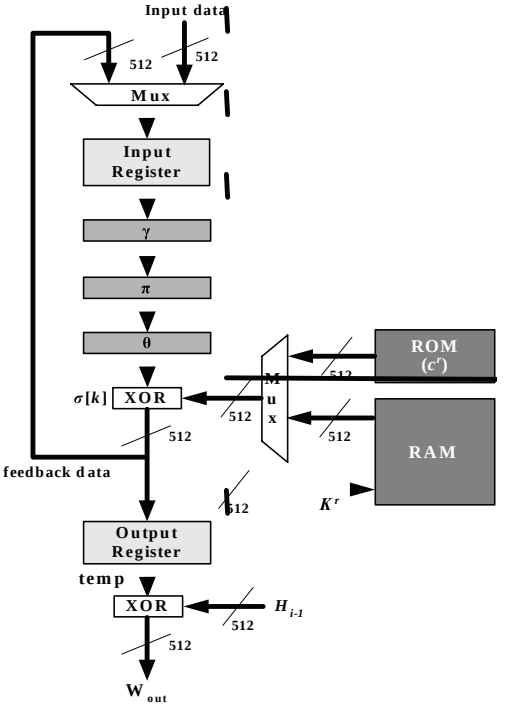
randomizing part in order to reduce the required hardware resources. The execution of the W block cipher on this implementation is performed in two phases. In the first phase, the round keys are produced and stored in the *RAM*. In the second phase, the hash value is computed. The algorithm specifies 10 rounds for the hash state. The *Input data* is the *initialization vector* (*IV*), in order to produce the round keys (first phase). The *Input Register* is used for buffering the algorithm *Input data*. The output data of the θ layer is bitwise XORed with the c^r constant. Each execution round lasts one clock cycle. After the first execution round, the first round key is stored in the *RAM*. It is used as input in the second execution round, through the multiplexer (feedback data), for the production of the second round key. This process is repeated 10 times (10 execution rounds) and lasts 10 clock cycles. The c^r constants are predefined and stored in the *ROM*. The multiplexer selects during the first phase the c^r constants, and during the second phase the round keys. The computation of the hash value is taking place during the second phase. In this phase, the Input data is the m_i block. The output data of the θ layer is bitwise XORed with the appropriate round key, which is stored in the *RAM*. After 10 execution rounds the *Output Register* latches the *temp* result. This result is bitwise XORed with the H_{i-1} value (in this case is equal to the IV) in order to compute the W_{out}. The W_{out} is XORed with the m_i (see figure 7), so the final, hash value H_i, is computed.

If another block m_{i+1} is required to be transformed, the previous process is repeated (by using as cipher key the H_i value). So, for t blocks the execution time is $20*t$ clock cycles. This has a result the total throughput of this implementation is half than the first implementation; however it needs almost half silicon area.

IMPLEMENTATION RESULTS AND DISCUSSION

The VIRTEX FPGA device used in order to evaluate the performance of the proposed implementations. Especially the XC4VLX100 device is used; this device belongs to a new family manufactured in 1.2 volts, 90nm triple-oxide technology and offers twice the performance, twice the density, and less than one-half the power consumption of

Figure 10. The implementation of the W block cipher suitable for applications with constrained silicon area resources



previous-generation devices. The basic building block of these devices is the DSP48 slice (see Xilinx, 2006). The purpose of this module is to deliver off-the-shelf programmable devices with the best mix of logic, memory, I/O, processors, clock management, and digital signal processing. In Figure 11 the DSP48 slice architecture is depicted. The Virtex-4 DSP slices are organized as vertical DSP columns. Within the DSP column, two vertical DSP slices are combined with extra logic and routing to form a DSP tile. The DSP tile is four CLBs tall. Each DSP48 slice has a two-input multiplier followed by multiplexers and a three-input adder/subtractor. The multiplier accepts two 18-bit, two's complement operands producing a 36-bit, two's complement result. The result is a sign extended to 48 bits that can optionally be fed to the adder/subtractor. The adder/subtractor accepts three 48-bit, two's complement operands, and produces a 48-bit two's complement result. Higher level DSP functions are supported by cascading individual DSP48 slices in a DSP48 column. One input (cascade B input bus) and the DSP48 slice output (cascade P output bus) provide the cascade capability.

The XC4VLX100 device used in this chapter contains 96 DSP48 slices.

Each one of the proposed implementations was captured by using VHSIC hardware description language (VHDL), with structural description logic. Both implementations were simulated to operating correctly by using the test vectors which are provided by the NESSIE submission package (NESSIE, 2004), and the ISO/IEC 10118-3 standard (ISO, 2003). Parts of the proposed implementations were designed by using two alternative techniques.

Figure 11. The DSP48 slice architecture

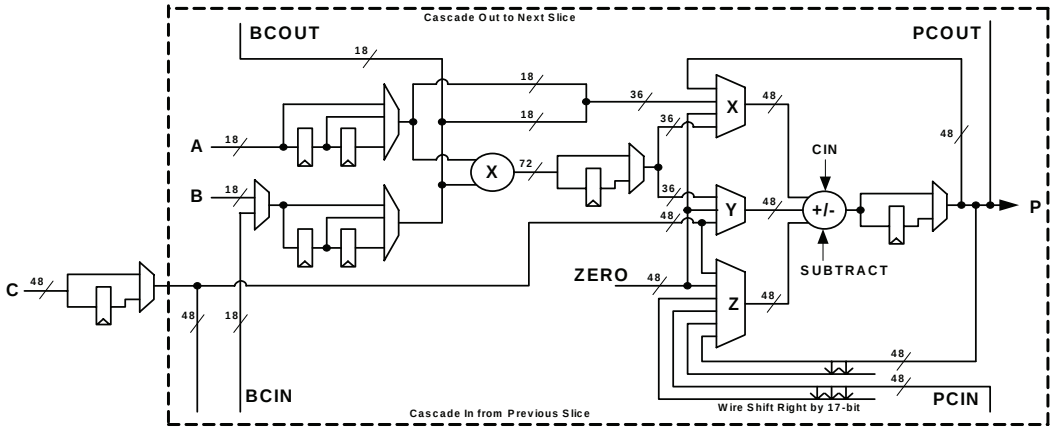


Table 1. Performance analysis measurements

Implementation	FPGA Device	Slices / BRAM	Frequency (MHz)	Throughput (Mbps)	Throughput / Slices
In McLoone et al. (2005) Unroll x 2	XC4VLX100	13210 / 0	47.8	4896	0.37
In McLoone et al. (2005) Iterative	XC4VLX100	4956 / 68	144	4790	0.96
In Pramstaller et al. (2006)	XC2VP40	1456 / 0	131	382	0.26
Author 1st_impl_BB	XC4VLX100	5021 / 0	236	12083	2.40
Author 1st_impl_LB	XC4VLX100	4848 / 0	337	17254	3.56
Author 2nd_impl _BB	XC4VLX100	3451 / 0	275	7040	2.04
Author 2nd_impl _LB	XC4VLX100	3376 / 0	313	8013	2.37

The 4-bit mini boxes (E, E^{-1}, and R) were designed by using LUTs and Boolean expressions. The usage of FPGA-LUTs does not increase the algorithm execution latency. Besides, the LUTs are implemented by using function generators. So, for the implementation of the Whirlpool hash function four alternative solutions are proposed.

Two performance metrics are considered: the area utilized and the throughput achieved by the implementations. The measurements of the performance analysis are shown in Table 1. And also, comparisons with other Whirlpool hash hardware implementations (McLoone et al., 2005; Pramstaller et al., 2006) are given. We symbolized as Boolean expressions based (BB) the mini boxes implementations by using Boolean expressions, and as LUT based (LB) the mini boxes implementations by using FPGA-LUTs.

Both implementations (1st and 2nd) were realized by the same FPGA device. The algorithm constants (c^r) are stored in a ROM which is implemented by using LUT. The 2nd implementation uses a 10x512-bit RAM in order to store the necessary round keys. This RAM is mapped to the 5K bits distributed RAM, and furthermore, none of the proposed implementations use block RAM (BRAM).

The 1st implementation requires 10 clock cycles for each block. So, the BB implementation throughput is 12 Gbps at 236 MHz clock frequency, and the LB implementation throughput is 17.2 Gbps at 337 MHz. The 2nd implementation was designed in order to support applications with area restrict requirements. It demands 20 clock cycles for each data block and requires less hardware resources. The BB implementation throughput is 7 Gbps at 275 MHz clock frequency and the LB implementation throughput is 8 Gb/s at 313 MHz.

In McLoone et al. (2005) two Whirlpool hash hardware implementations are presented. In the first one, two rounds of the block cipher W are unrolled and during one clock cycle two rounds are performed. This method reduces the overall latency of the design, but it will also result in a reduction in frequency. In order to compute the final hash output needs to be iterated five times. This implementation achieves a throughput equal to 4896 Mbps at 47.8 MHz. The second one is iterative implementations with algorithmic latency equal to 10 clock cycles. The major difference with previous and also with author implementations is that use BRAM in order to implement the S-boxes. The throughput of this implementation is 4790 Mbps at 144 MHz. An 68 BRAM is also used.

In Pramstaller et al. (2006) a very compact Whirlpool hash hardware implementation is discussed. This design has different philosophy than the implementations in this chapter and uses an innovative state representation that makes it possible to reduce the required hardware resources

remarkably. The complete implementation into XC2VP40 VIRTEX FPGA requires 1456 CLB-slices and no BRAMs. It achieves a throughput equal to 382 Mbps at a clock frequency equal to 131 MHz.

As Table 1 shows that the author's proposed hardware implementations of the Whirlpool hash function clearly outperforms all the others implementations. The proposed implementations are faster by a factor range from 1.5 to 45 times. Especially comparing with implementations in McLoone et al. (2005) some important results can be extracted. Firstly, the two implementations in McLoone et al., use the same FPGA device with the proposed implementations reported in this chapter. So, any comparisons are absolutely fair and accurate. Secondly, by using FPGA-LUTs much better results are achieved in both time performance and area requirements. Finally, about the ratio throughput per slice, that measures the hardware resource cost associated with the implementation resulting throughput and it is proven that the proposed implementations in this chapter philosophy matches better than the implementations in McLoone et al., to the FPGA characteristics (due to the high throughput per slice ratio). The design in Pramstaller et al. (2006) achieves a throughput equal to 382 Mbps at 131 MHz slower by a factor range from 18 to 45 compared with the implementations in this chapter. Although, as I have already mentioned, this design has different philosophy and requires only a small amount of hardware resources.

Besides, comparisons with some other hash families' implementations (Ahmad & Shoba Das, 2005; Deepakumara et al., 2001; Dominikus, 2002; Grembowski et al. 2002; McLoone & McCanny, 2002; Sklavos & Koufopavlou, 2003, 2005; Yiakoumis et al., 2005) (the faster implementations of other hash families' are collected) are given in Table 2 in order to have a fair and detailed comparison with the proposed implementations.

From Table 2, it is obvious that the Whirlpool implementation performs much better in terms of throughput, comparing to all the previous hash families published implementations (Ahmad & Shoba Das, 2005; Deepakumara et al., 2001; Dominikus, 2002; Grembowski et al., 2002; McLoone & Mc-

Table 2. Comparisons with other hash families' implementations

Implementation	FPGA Device	Slices	Frequency (MHz)	Throughput (Mbps)
MD5 (Dominikus, 2002)	XV300E	1004	42.9	146
MD5 (Deepakumara et al., 2001)	XV1000FG680	4763	71.4	354
SHA-1 (Yiakoumis et al., 2005)	Virtex-II	854	162	1036.8
SHA-2 (512) (Sklavos & Koufopavlou, 2003)	XCV200	2237	75	480
SHA-2 (512) (Grembowski et al., 2002)	XCV1000	3441	55.5	670
SHA-2 (512) (McLoone & McCranny, 2002)	XC4VLX100	2734 + 2 BRAM	~	854
SHA-2 (512) (Ahmad & Shoba Das, 2005)	STRATIX EP1S10F484C5	4229 LEs	47.9	1226
RIPEMD-128 (Sklavos & Koufopavlou, 2005)	2V250FG456	1814	78	2300
RIPEMD-160 (Sklavos & Koufopavlou, 2005)	2V250FG456	2014	73	2100
Author 1st_impl_BB	XC4VLX100	5021	236	12083
Author 1st_impl_LB	XC4VLX100	4848	337	17254
Author 2nd_impl_BB	XC4VLX100	3451	275	7040
Author 2nd_impl_LB	XC4VLX100	3376	313	8013

Cranny, 2002; Sklavos & Koufopavlou, 2003, 2005; Yiakoumis et al., 2005) . The implementation in McLoone and McCranny (2002) uses the same FPGA device as the proposed implementations in this chapter. It also, requires more hardware resources compared with the other hash families' implementations. This is a logical result of the algorithm philosophy and not an implementation trade-off. Finally the Whirlpool has the smaller algorithm execution latency. It needs only 10 clock cycles in order to transform each block compared with the 64 clock cycles of the MD5, and SHA-2 (256), and 80 clock cycles of the RIPEMD-160, SHA-1, and SHA-2 (384, 512). This is an important advantage of the hardware implementation.

CONCLUSION

The Whirlpool hash function is the most recent hash function to be standardized. It was selected to be included in the NESSIE portfolio of cryptographic primitives. An efficient architecture and VLSI implementations for this hash function are presented in this chapter. Two architectures for *W* block cipher are introduced. The first one is appropriate for high speed applications since the round keys are produced on the fly while the second one is appropriate for area restricted devices. Parts of the proposed implementations were designed by using two alternative techniques. The 4-bit mini boxes (*E*, E^{-1}, and *R*) were designed by using LUTs and Boolean expressions. So, four implementations have been introduced and each specific application can choose the appropriate speed-area, trade-off implementation. The achieved throughput for the proposed implementations ranges from 7 Gbps to 17.2 Gbps. These hardware architectures and implementations are significantly faster than any other previous reported implementations of the algorithm and they are also up to 16.5 times faster than hardware implementations of other hash functions.

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KEY TERMS

Cryptography: In modern times, cryptography has become a branch of information theory, as the mathematical study of information and especially its transmission from place to place. Cryptography is central to the techniques used in computer and network security for such things as access control and information confidentiality.

DSP48 Slice: DSP48 slice is the basic building block of XILINX VIRTEX-4 FPGAs.

Field-Programmable Gate Array (FPGA) Device: FPGA device is a semiconductor device used to process digital information, similar to a microprocessor. It uses gate array technology that can be reprogrammed after it is manufactured, rather than having its programming fixed during the manufacturing—a programmable logic device.

Hardware Implementation: Hardware implementation is the building of the blocks of digital chip (either ASIC or FPGA) design and it relates them to the hardware description languages that are used in their creation.

Hash Function: Hash function is a function that maps an input of arbitrary length into a fixed number of output bits, the hash value.

New European Schemes for Signatures, Integrity, and Encryption (NESSIE): NESSIE was a European project that was responsible to introduce new cryptographic primitives with high security levels.

Whirlpool Hash Function: Whirlpool hash function is the most recent hash function to be standardized. It was selected to be included in the NESSIE project of cryptographic primitives.

Section II
Security in 3G/B3G/4G

Chapter XVIII
Security in 4G

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ABSTRACT

The fourth generation (4G) of mobile networks will be a technology-opportunistic and user-centric system combining the economic and technological advantages of different transmission technologies to provide a context-aware and adaptive service access anywhere and at any time. Security turns out to be one of the major problems that arise at different interfaces when trying to realize such a heterogeneous system by integrating the existing wireless and mobile systems. Indeed, current wireless systems use very different and difficult to combine proprietary security mechanisms, typically relying on the associated user and infrastructure management means. It is generally impossible to apply a security policy to a system consisting of different heterogeneous subsystems. In this chapter, we first briefly present the security of candidate 4G access systems, such as 2/3G, wireless LAN (WLAN), WiMax, and so forth. In the next step, we discuss the arising security issues of the system interconnection. We namely define a logical access problem in heterogeneous systems and show that both the technology-bound, low-layer and the overlaid high-layer access architectures exhibit clear shortcomings. We present and discuss several proposed approaches aimed at achieving an adaptive, scalable, rapid, easy-to-manage, and secure 4G service access independently of the used operator and infrastructure. We then define general requirements on candidate systems to support such 4G security.

GENERATIONS OF PUBLIC LAND MOBILE NETWORKS

From 1G to 2G

The first generation of public land mobile networks (PLMN) is characterized by the fact that both control channels and traffic channels are analog. Voice (commonly at 3 kHz) and data (if any) are frequency-modulated on a carrier. Today, these networks are usually summarized under the common name first generation (1G) although there are different analog network standards like Nordic mobile telephony (NMT), American mobile phone system AMPS), and total access communication system (TACS).

NMT was the first commercially operated PLMN (1981). NMT uses two different frequency bands about 450 and about 900 MHz (NMT 450 and NMT 900). NMT900 was introduced in 1986 as a result of the fact that the number of channels in NMT 450 was insufficient. NMT 900 has been implemented in Europe, the Middle East, and Asia.

AMPS was specified by the U.S. consortium TIA/EIA/ANSI. The first AMPS network became operational in 1984. In 1988, an extension providing additional frequency bands was added (E-AMPS). AMPS networks are found in the Americas, Australia, and in Asia.

TACS is a modification of AMPS aiming at the British market, where the standard was operational in 1985. TACS also received a wider frequency band in 1988, E-TACS. Since that time, TACS has spread to many countries around the world.

In 1982, at the time of the commercialization of the first 1G networks, the Groupe Spécial Mobile was formed at CEPT (*Conférence européenne des Administrations des Postes et des Tèlécommunications*, the creator and standard-body predecessor of today's *European Telecommunications Standard Institute, ETSI*), with the task of developing a Europe-wide standard for cellular communication. In other words, the scope here was to provide the same service (voice) by a new, universal system.

In 1987 the CEPT working group decided to build a digital, narrowband time division multiple access (TDMA) system. In 1990, ETSI published Phase I of the GSM system specifications. Three frequency bands have been defined for global system for mobile communications (GSM) usage: 900MHz, 1800 MHz, and 1900 MHz. The corresponding standards are similar, aiming at

Table 1. Ten years cycles in the mobile networks (from a European view)

Year	Milestone	Cycles		
1981	*Commercial deployment of NMT: **1G start***	1G to 2G: 10 years		
1982	Creation of Groupe Spécial Mobile at CEPT			
1984	Commercial deployment of AMPS networks in the US			
1986	Big number of users leads to NMT extensions			
1988	Big number of users leads to AMPS extensions			
1989	European Union RACE Project "invents" UMTS		3G conception: 10 years	
1992	World Administrative Radio Conference (today: WRC) allocates 230 MHz to Future Public Land Mobile Telecommunication System (FPLMTS).			
1992	*Commercial deployment of GSM: **2G start***			2G to 3G: 10 years
1994	Second wave of UMTS research projects			
1995	RACE vision of UMTS			
1996	Creation of UMTS task force			
1996	*Digital overcomes analog*			
1997	Establishment of the UMTS Forum			
1999	UMTS decision			
2000	WRC designates IMT-2000 extension bands			
2002	*Commercial deployment of UMTS: **3G start***			

wide-range (GSM 900) and dense-area (GSM 1800/1900) deployments respectively. The first commercial GSM services were launched in the middle of 1991, thus marking the start of the second generation (2G) era.

GSM was the first completely digital PLMN. It is thus naturally a revolutionary approach, as compared to its analog predecessors. GSM defines a series of improvements and innovations compared to previous cellular networks; aiming for an efficient use of the available spectrum; secure transmissions; an improvement in voice quality; a reduction in the cost of handsets (using very large-scale integration [VLSI]); infrastructure and management; an ability to support new services; and a full compatibility with *Integrated Services Digital Network (ISDN*) and with other data transmission networks. Another basic characteristic of the system is called *international roaming*, that is, the possibility for the mobile user to access GSM service even when he/she finds himself/herself physically outside the coverage area for which he/she is subscribed, registering as a "visitor." Provided that the necessary business contracts exist, the roaming is completely automatic. In addition to roaming, GSM offers new user services, including data transmission, fax service, and short message service (SMS).

Thus, in Europe one completely new standard has replaced different existing ones. Almost the contrary happened in the U.S.: the quasi unique AMPS has been replaced by a variety of (at least partially) incompatible, (partially) digital systems: N-AMPS, D-AMPS (IS-54, IS-136), PCS (IS-95), GSM 1900, Omnipoint, and PACS.

The variety of incompatible networks and the increasing popularity of data services have motivated and much influenced the work on the third generation (3G) of mobiles. In 1992, at the same time as the commercial deployment of first 2G networks started, the International Telecommunications Union (ITU) allocated frequency ranges for the next generation of PLMN (then called FPLMTS) thus providing an international common base for the 3G. Finally, in 2002 the first commercial 3G networks were commercially deployed in Japan.

Table 1 summarizes the history of the PLMN development from the European point of view as presented in Pereira (2000). In particular, it illustrates the repeating approximate 10-year cycles both in the conception phases and in the generation lifetimes.

The Third Generation of PLMN

The 3G of mobiles was expected to be the future global standard for the integrated voice and data communications. 3G was designed in the last decade of the 20th century with the goal to provide enhanced wide-range voice and data services. But it turns out that it changes little in the actual user experience.

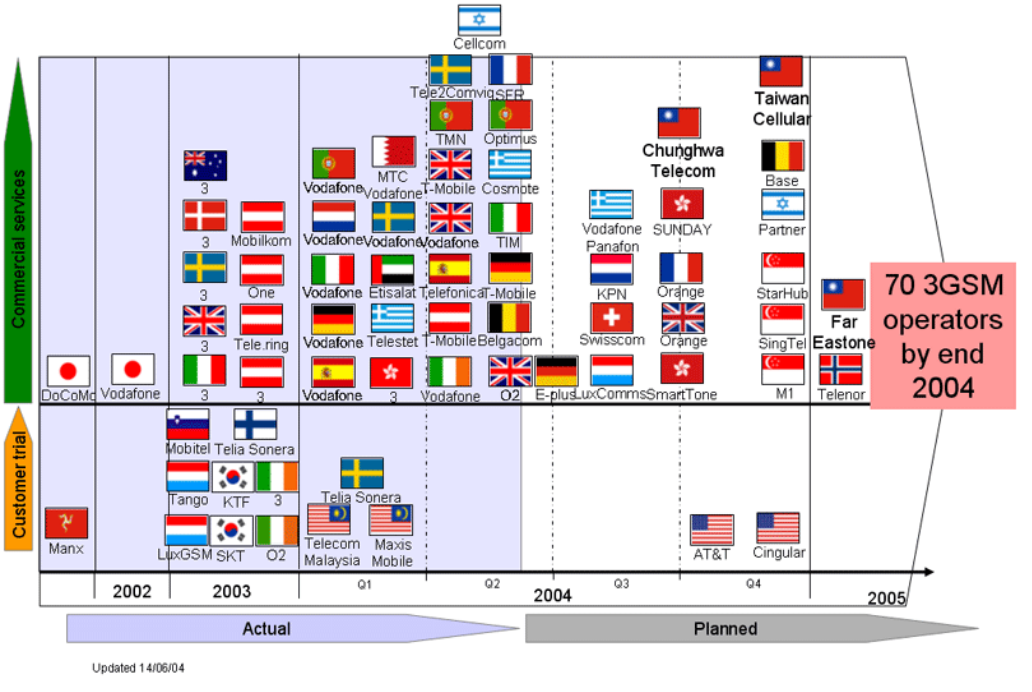
Technically, 3G design mainly aimed at the improvement of the radio link performance in the 2G scope. Although the developed standard features drastically improved data rates as compared to 2G, from the point of view of the data services the practically offered data rates can be still considered scarce. This can be observed in a direct comparison to the development of the wired technologies providing home Internet access. From 1994 until 2004, the phone-line Internet access technologies have evolved from V.34 modems (28.8 kbps) over V.90 (56 kbps) to cable (1-2 Mbps shared) and ADSL (originally 500 kbps, 2004 up to 10 Mbps). This means an almost 350-fold increase in 10 years. In the same period, the data rate of the wireless cellular access has not been able to keep up the pace. From the original GSM CSD service introduced in 1994 and providing 9.6 kbps, the cellular systems evolved over General Packet Radio Service (GPRS) (about 64 kbps in practice) to EDGE/cdma2000 RTT-1X (typically about 100-130 kbps). The 3G (e.g., UMTS) provides about 300 kbps in practice. This corresponds to a 30-50 fold increase in the same decade. Moreover, the provided data rates highly depend on the network operator's overall capacity, the number of users in the cell and the distance to the base station.

However, the relatively limited data rate is not the only problem of the 3G data service. Because of the vast, national-scope infrastructure, and many intermediate nodes, the user experiences

high network latency (e.g., from the point of view of IP, the whole 3G infrastructure is one link). GRPS and EDGE often exhibit network *round trip times* (RTT) of 600 ms and more. UMTS links are expected to be better, but they still have RTT of about 200-250 ms. The wideband code division multiple access (W-CDMA)/high speed downlink packet access (HSDPA) service, defined in the fifth release, is expected to have more than 100 ms RTT, that is, almost an Internet-level RTT. Such high network latencies are inappropriate for certain application classes: interactive applications imply latency constraints that typically lie under the 300-400 ms overall RTT proposed by 3G (the end system is not necessarily within the UMTS backbone and thus the typical Internet RTT of about 100-200 ms has to be added to the 3G latency). For example, voice over IP (VoIP) and similar applications (videoconferencing, etc.) require an RTT to be under 250 ms; in some existing popular interactive online games (e.g., id Software's Quake, etc.), the maximal acceptable RTT to the game server is required to be under 100 ms in order to provide a fair chance of winning and a good game experience.

Furthermore, by its design 3G targets telecommunications providers. Like 2G, 3G uses a license model to prevent random medium access by non-authorized parties. Since the licenses are expensive (Van Damme, 2002), in reality this implies a major telecom operator with a mammoth infrastructure behind every 3G RAN. To fulfill the requirements of such an authority, the 3G RANs are designed to be reliable and manageable and to support different qualities of service. This justifies the high cost of the 3G equipment. At the same time, this limits the competition on the market to few license holders who not only have invested a lot in the infrastructure but also have paid a high price for the license. The operators have to amortize this fixed cost and the current variable maintenance and management cost over the user services provided by the infrastructure. Thus, 3G RAN access is likely to remain costly. It is unclear if attractive unlimited flat-line pricing models (like in xDSL) are applicable to such infrastructures. Current per

Figure 1. 3G: Current and planned UMTS launches



byte (or even per minute!) pricing seems hardly suitable for the always-on paradigm.

A consequent national-scope investment is needed for 3G advantages to materialize (both for users and for providers). This is however difficult to afford, especially in developing countries where big investments are particularly risky. In a focused coverage, 3G comes at a very high cost per bit compared to other, more data-centric technologies like local or metropolitan area networks. That is one of the reasons why the 3G systems had a difficult start. They are primarily being deployed in Japan, South Korea, Taiwan, Hong Kong, Indonesia, a few countries of South America, Australia, New Zealand, western Europe, and North America (CDMA Development Group, n.d.; GSM Association, n.d.). Figure 1 (GSM Association, n.d.) summarizes the actual and planned commercial launches of the 3G system from the 2004 European point of view (W-CDMA/UMTS). It shows that the developed countries prevail.

Although the slow 2G-3G transition process started in 2003-2004, so far the 3G systems do not seem suitable to provide a broadband data access service deployment. In the developed world, these are often considered technologically inadequate (users perceive it as a better 2G). For the developing world, the technology needs major investments. Thus, a new, more flexible technology is necessary, allowing new usage scenarios and business models.

The Anticipated 3G to 4G Transition

In regards to 3G, the observed 10-year cycles seems to continue. The first research concepts aiming at 3G appeared about 1989. The spectrum was reserved by ITU-R's World Radiocommunication Conference (ITU-R Radiocommunication Conference, 1992), that is, at the same time as the first 2G networks were deployed. The active technological development of 3G started with the creation of the UMTS task force in 1996 and culminated in the UMTS decision in 1999. The largest parts of the standards were accomplished by then.

Consequently, the first projects naming fourth generation (4G) started in 1999 and the first dedicated thoughts about beyond 3G (B3G) and 4G systems appeared in the international research press about 2000-2001 (Bria et al., 2001; Evans & Baughan, 2000; Pereira, 2000; Raivio, 2001; Varshney & Jain, 2001), that is, just before the first commercial 3G networks were deployed in Japan. In 2000, the WRC allocated 3G extension bands, which were to be used in the B3G scope. All this corresponds to the 10-year cycles illustrated in Table 1.

Continuing along this line, the concrete shapes of 4G should be clarified by the end of 2007 and the active 4G vision refinement should start about 2007-2008. This should be finished roughly by 2010, with several detail issues being addressed in the following years. The first commercial systems could then be operational by 2012. However, this presumes that no additional delays occur.

Possible Delays

At least in Europe and in the U.S., the 3G deployment seems to be delayed. Indeed, by the end of 2004, not all western European countries started the 3G deployment. Also, the deployment process is starting quite slowly, often being limited to some few centers. The critics of 3G claim that the reasons for this could be in the developed technology itself. Indeed, one could argue that 3G (in Europe: UMTS) is too complicated and too costly to become successful. One could also criticize the fact that the original goal of creating one common global standard has not been achieved since different concurrent versions of 3G are being standardized and deployed, in some extreme cases within the same country (e.g., Japan has deployed both cdma2000 and W-CDMA). However, the deployment of the alternative technologies (like e.g., 802.11 hotspots or WiMax) also lags behind the expectations that have predicted a WiFi-boom and hotspot number explosions by 2005, which so far have failed to become true. There is no doubt about the popularity of WiFi. However it is not booming, it is being carefully developed. The real reasons thus could be either of a social (e.g., a simple current disinterest in mobile data) or of an economic nature (too costly in deployment, too risky for operators; too costly, too complicated for users, etc.).

We tend to think that economic barriers prevail. Indeed, businesses have so far often expressed their need for mobile communications development. This has been much discussed in different business scopes: home- and telework, instant data access for mobile sales personnel, fleet management, reduction of infrastructural costs, globalization, and so forth. With the further development of the Internet and the associated technologies, private users are also likely to be interested in services such as mobile e-commerce, online gaming, private communications (e.g., voice or instant messaging), various personal and business data exchanges, and so forth.

The telecommunication crisis initiated by the complete flop of the exaggerated initial Internet business activities (often referred to as the *bursting of the Internet bubble*) could have been one of the key economic factors responsible for the observed 3G deployment delays. Indeed, the investments in the IT and telecommunication sectors have since radically switched from headlong promiscuity to skeptical cautiousness. From the European point of view, the starting crisis was amplified by the UMTS license auctions in 2000-2001 raising cumulatively over 100 billion USD in the Western European countries (Van Damme, 2002).

The paid spectrum prices washed away much of the liquidity of the Western-European telecommunications operators. Yet, this liquidity was necessary for the deployment of the network (infrastructure updates and add-ons). Since the UMTS cannot substantially improve the GSM voice service as such, the only added value of the UMTS is in the improved data services. Hence, compared to classic GSM offerings, the paid auction price for the UMTS licenses must be amortized over time over the new services, which UMTS is just about to propose. However, this could render these new services particular expensive.

4G: A TECHNOLOGY-OPPORTUNISTIC, USER-CENTRIC SYSTEM

4G Expectations

With the ongoing globalization, world-wide communications become an essential service. The 3G, meant to provide a global communications standard, has mostly failed to do so. Instead, it now uses different standards in different countries. Moreover, 3G remains a closed "big company" telecommunications forum. That results in the situation where users still need costlier multi-band, multi-technology handsets, yet they cannot access the 3G services using other devices over newer radio access networks (RANs). To provide users with a world-wide service we need open flexible standards, also suitable for the Internet and data communications deployment in the developing countries.

At the other end, personal communications are being rapidly developed using short range radios. These need to be considered for the next generation communications because their rapid development is a fact (Raychaudhuri, 2002). The existing personal area networks (PAN) and LAN technologies are often used for device-to-device data transfers but can easily do more than that. Wireless headphones, handsets, and PDAs can already build personal networks capable of data and voice transport. In the home area or in vehicles (e.g., personal cars), this can be extended to LAN-like communications. The aim here is to give users access to their data independently of the device currently in use. So, handsets can be asked to dial numbers stored in the home PC and to direct the voice flow to the wireless headphones. Wireless sensors are already available, for example, for outdoor weather condition measurements. Wireless sensors are used more and more in cars. They are also expected to be further developed for home users (intelligent home). This underlines the increasing part of the machine-to-machine (M2M) and network-to-network (N2N) communications in the future communications landscape.

The obviously challenging scenario is to provide users with a bidirectional communications possibility to their personal Intranets independently of their location (anywhere), thus combining the two topics discussed previously. These WAN/MAN/LAN/PAN spanning communication sessions have to be secure, reliable, and economically reasonable. Also, communications become ubiquitous. The used technology needs to be able to reply to this challenge, providing the best available connection anytime, any place. Existing standards do not allow for this usage.

However, it is not a matter of contention between these existing standards. They are more and more understood as complementary. Indeed, the WLANs can easily provide a true LAN experience in limited areas at a low cost while 3Gs RANs are designed to provide true mobility, quality of services and vast coverage. The idea to try to integrate both technologies is thus straightforward.

Taking into account the previously observed cycles and the current delays, we could try to compile a prognosis on the B3G and 4G development in the next decade. The current situation and our forecast are illustrated in Table 2.

The convergence between the different infrastructures will start because of the economic and technological limits of the used technologies. Big telcos will try to reduce their service cost by integrating alternative transmission technologies as radio access networks (RAN) into their 3G infrastructure (e.g. UMA-like). However, this integration will still be much more complicated and costly than a new deployment possible for a small wireless internet service provider (WISP). At the same time, the small WISPs will encounter increasing management problems with the growing user basis and the user traffic. It will hardly be reasonable to add a 3G infrastructure upon the existing one as the control plane. Given the lack of standardized methods, the alternative infrastructures are thus likely to be managed in a proprietary way, requiring specific access methods. This will produce the demand for standardization.

Because of the true need for mobile broadband data access and the scarce spectrum of 2G, the 3G will be eventually deployed in the business centers of the developed countries despite the currently observed delays. In Europe, this process could be further promoted by governmental policy in some countries planning to partly reimburse some license fees. However, the delays and the high license fee (Van Damme, 2002) have already motivated the development of and the investments in the alternative transmission technologies, for example, IEEE 802.11 and IEEE 802.16.

Table 2. Possible 3G development in the next years

Year	Milestone	Cycles
2003	*European 3G start*	3G to 4G: 10 years
Until 2005	Different 4G visions and early 4G research projects	
2006	3G deployment in all business areas in the developed world	
2006	Broad deployment of alternative technologies (from WiFi to WiMax, etc.)	
2007	Further deployment, different UMTS updates (HSDPA, HSUPA) and integration of alternative technologies in the UMTS infrastructure	
2009	Convergence of different 4G views implied by the economic and technological factors	
2010	The high popularity of data services shows 3G transport limits and WiMax/WiFi management limits (security, mobility, usability, etc.)	
2011	Deployment of first B3G (3.5G) systems	
2011	Establishment of a 4G forum	
2012	Mature technical drafts of 4G systems integrating different technologies	
2014	*First commercial 4G services*	

This development, if commercially successful, will lead to a situation with several parallel infrastructures installed in the European centers by 2008-2009. While the 3G infrastructures will be homogeneous, they are likely to remain more expensive. The alternative offerings will be cheaper but are not likely to provide neither the same service quality nor the same coverage. Because of the required spectrum licenses, the same national-scope operators will own the 3G systems. The alternative technologies are license-free and thus enable a free network deployment. These can be owned by both global big telcos and small local WISPs.

Users will buy newer products equipped with further wireless technologies. Deploying these products at home, users will be interested in accessing the combined service offers. Different devices will be capable of several access methods (e.g., a wireless ADSL router). Users will be incited to open their hotspots for the usage by the others. For instance, a major French telecom provider proposes a reimbursement plan for its ADSL users if they provide WLAN access to its cellular customers over such devices. At the same time, alternative technology operators are forming roaming organizations and user communities, aiming for the same results (see WeROAM, Fon communities, etc.)

Meanwhile, the research will push towards unified and concrete B3G and 4G views. To protect the investments, the deployed alternative infrastructures are likely to be given the necessary attention in this development process. The result will likely be a system providing for a convergence between the different technologies.

While the new 4G architecture is being conceived and is maturing technologically, 3.5G systems are likely to appear on the market by 2010 at the latest, filling the gap between LAN-experience and manageable. These updates of the radio link and of the backbone infrastructure could provide the basis for the later expected 4G much in the same manner as GPRS/EDGE (2.5G) have required and accomplished the necessary infrastructural changes for the transition process from 2G to 3G. The commercial and technological convergence and the available B3G systems will provide the drivers for the establishment of an industry group (e.g., 4G forum) that will be given the task of 4G system standard development. Based on the situation and the previously accomplished research, it could produce mature system drafts by 2012 and the first commercial 4G deployments could start about 2014.

Our 4G Vision

Our vision is motivated by the previous work and the ongoing development of the global telecommunications networks, in particular of the Internet. It respects the fact of the proliferation of the Internet technology in all telecommunications branches and is similar to the All-IP approach when used for data transport.

Learning from 2G and 3G experiences, 4G envisages an architecture that allows the maximum possible infrastructure reuse. The idea is to minimize a risky engagement with a particular technology and to guarantee the long-term flexibility for the involved authorities. We believe that the versatility here can provide an enhanced flexibility both technologically and from the business point of view. This ultimately market-driven solution should be capable of providing any service in any manner, restricted solely by user's demand and not by any technological factors.

From Service-Centric to Data-Centric Approaches, from Technology-Centric to User-Centric Approaches

The classic telecommunications industry approach dominated by the national-scope telecom operators with the well-managed infrastructures currently cannot provide a cost-effective focused access to Internet services. This is particularly true for the developing countries where neither new installations nor massive updates of the existing infrastructure can be afforded.

In its initial collaborative work, the telecommunications industry was much influenced by the dominating demand for the voice telecommunications. The 1G and 2G systems were originally designed to provide one single service: the mobile voice telephony. Their system design was

service-oriented. As a result, the conceived core infrastructure is circuit-oriented and the wireless link's capacity is tailored to the voice-implied bandwidth requirements. Due to these properties, 2G currently provides a reliable voice service; it is however quite difficult to reuse this infrastructure for other purposes. However, deploying a new infrastructure for every service is not scalable and financially impossible. Especially with the modern digital technologies, it is much more efficient to reuse the same infrastructure for different services.

3G development is an example of a *network-oriented design* process (sometimes also called operator-oriented design). It is a step ahead from the service-oriented design of the 2G system since it explicitly provides for infrastructure reuse for various services. Principally aiming at operators and networks, such design tries to respond to operator's management requirements. It thus specifies parts of the network core, producing homogeneous technologies comprising everything the operator has requested. According to this design paradigm, the 3G technologies deliver voice and data within the same infrastructure. In presence of an existing voice-oriented 2G infrastructure this renders the only added service—the mobile broadband data—quite expensive in itself. The operators have to amortize the network deployment and the license cost over the new service. Thus, from the user's point of view, this new service is often perceived as too expensive.

To be able to provide cost-effective data services at any chosen place in the world we need more user-oriented and data-centric approaches than what 2G and 3G paradigms deliver. At least in the mid-term, the hope here lies in a more opportunistic approach from the technological point of view. Indeed, the user typically does not care about who provides a particular service and how. The user cares about the availability of services, their performance (throughput, latency, etc.), the quality of service (QoS) (i.e. the performance and the variation of the performance factors), the ease of use, and service prices. Accordingly, the *user-oriented design* tries to respond to these user wishes assuring the possibility to freely choose an available service. Choice, as the driving factor for the competition, plays a crucial role in this scope since it results in better and cheaper technology.

From the system's point of view, the resulting overall architecture delivers very different services through completely heterogeneous access networks (ANs). User-oriented design has to cope with the question how to manage the system and how to provide user services with an expected quality. The management is important because a good management reduces the operational costs. The provision of the expected quality is the main factor for the user satisfaction.

Such architecture could help to achieve more infrastructural and architectural flexibility providing a free technology choice for the local operators and thus, in the final run, reducing the costs and offering more choices for the users. By featuring more flexibility, this step to further diversification gives new opportunities and could help, for example, to reduce the cost or to mitigate some aspects of the digital divide problem.

At the same time, this task is not technologically simple. As could be seen from the previous examples, the service-oriented design approach is a straightforward technological way to conceive a network dedicated to the needs of one single service. Provision of more services within the same infrastructure makes it more difficult to assure that every service individually is provided in a satisfactory way. We can generally allege that the QoS in the multi-services network is more difficult to maintain because very different requirements have to be fulfilled by the same infrastructure. Yet, owing to this common homogeneous infrastructure, with the network-oriented design it is still relatively easy to conceive systems enabling a comprehensive network management. The necessary dynamic infrastructure-to-service adaptation (e.g., for QoS) can then be achieved using the integrated management functions.

The step to the user-oriented design potentially implies a broad diversification of data transport technologies providing different services. Thus, the resulting systems inherit the problems of the dynamic per-service QoS provision. Additionally, we run into difficulties trying to consolidate all

these different technologies and make them do what the operator wants. This applies to the network management in general. In particular, it concerns the mentioned QoS provision problematic and also raises diverse security considerations, both of the operators (infrastructure control and protection, resource usage control, accounting and billing) and of users (data confidentiality, location privacy, flawless billing).

Hence, the user-oriented design opens new possibilities but potentially results in a heterogeneous environment. To be deployed and maintained by the operators, this environment needs to be understandable, manageable, flexible, and secure. To be used, it needs to be user-friendly, reliable, and fair. In particular, users should be able to use different services over different infrastructures in the same, familiar manner.

Thus, we need to develop more flexible infrastructures and more sophisticated mechanisms for infrastructure access incorporating but hiding the whole technological complexity. These mechanisms should provide adaptability to both users and contents. Here we concentrate on heterogeneous network access mechanisms and the necessary corresponding network management functions in the scope of the future integrated environments.

Multi-Provider Network Environment

For 4G, the accent lies on users and the requested services (Pereira, 2000). For the flexibility and cost reasons, the 4G architecture has to be able to integrate different technologies to provide *services* to users. Services are divers offerings, commercial or free, ranging from a basic connectivity (e.g., to the Internet) to more sophisticated services such as voice calls or instant messaging (IM). To provide more complex services, some providers can use services proposed by other providers.

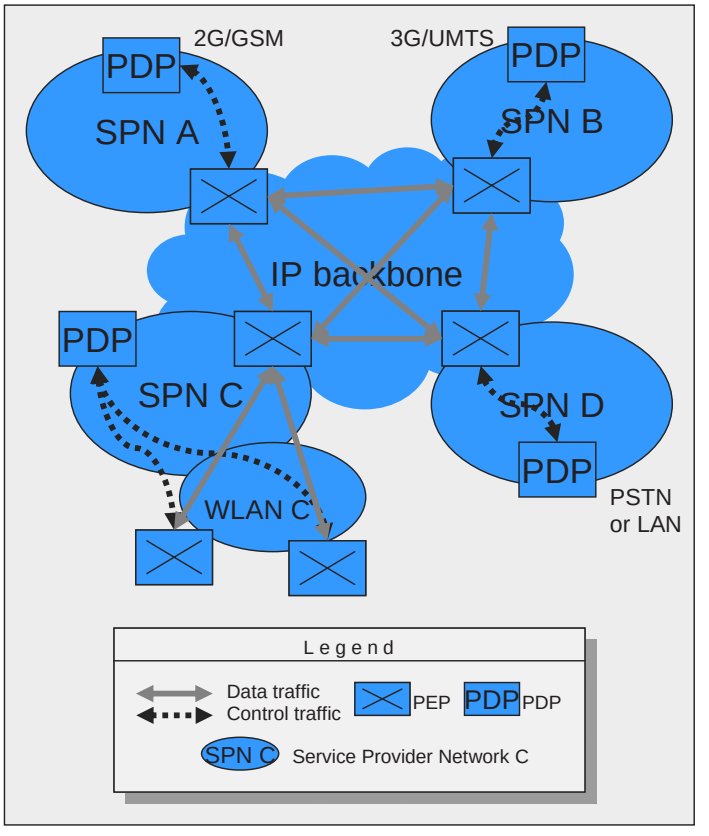
We see 4G as a potentially open, heterogeneous, user-oriented architecture, consisting of different service and ANs. These networks are operated by different authorities. We call such authorities *service providers*[1] if access to services is possible over their respective infrastructures or *networks*. The global 4G architecture is shown in Figure 0-1. It is composed of a panoply of service provider networks (SPNs) connected by an IP-based core network for any global data exchanges. SPNs principally support different wireless ANs. AN technology can range from personal to wide area networks.

Each provider may, but is not required to, have its own *users* and propose multiple services over different ANs. Users are defined as logical system identities subject to the service contract between two legal bodies, one representing the provider and the other representing the served user. This definition implies that every user corresponds to a *service contract* with exactly one provider.[2] Note that this contract requirement does not imply any price models or restrictions. Since every user corresponds to one legal body, we use these terms interchangeably in the rest of the document unless explicitly distinguished.

The service contract provides the trust relationship and the set of authorizations. From the user's point of view, the provider from the corresponding service contract is called *home provider*. If a user uses a provider only for user identification, authorization, and billing services, we call this provider a *virtual operator*[3] *(Zhang, Li, Weinstein, & Tu, 2002)*. Virtual operators (VOs) can but do not need to have their own infrastructures. Typical VOs are, for example, 2G or 3G providers (because of their existent user database), miscellaneous resellers but also credit card issuers, banks, public remote authentication services, and so forth.[4]

Providers may (but are not required to) serve users for whom they are not home providers. Providers may propose access to services in their own and in other infrastructures (e.g., in the Internet or in user's home network). The necessary network interconnection can be based upon private infrastructure interconnections of several providers or it can be based on a public backbone like the Internet. This and other definitions, for example, service level agreements, price agreements, mutual agreements on user authorization in visited networks, and so forth are subjects of so-called *roaming agreements* signed between the legal bodies representing the providers. Using these roaming agreements, providers can verify identities and profiles of visiting users whom we call *visitors*.

Figure 2. Global system architecture



The users who do not have any verifiable service contracts may be treated as *guests*. Guests are users with special authorizations (profiles), locally and freely defined by any operator. These are thus local users and will not be treated differently in the following.

SPN Organization and Management

Management tasks in the SPN are carried out by the SPN owner, that is, the provider. The actions are based on the management policies that reflect provider and user requirements. For this purpose, providers deploy policy decision points (PDP), that is, logical entities capable of taking completely automated or assisted decisions based on the observed network situation and the defined policy. Policy enforcement points (PEP) are installed in the control equipment to enforce made decisions. In particular, PEPs are installed in the edge equipment.

SPNs are supposed to be trusted, non-public networks with appropriate protection measures. User traffic is to be strictly separated from the management traffic. The internal communications are IP-based. Inter-SPN management traffic can be protected by IP security (IPsec) (Kent & Atkinson, 1998), or by using dedicated protected links (L2 virtual private network [VPN] services, trusted sub-infrastructures, etc.)

Internal SPN architectures are deliberately left open. The protocols and mechanisms regarding PEP, PDP, measurements, and so forth do not need to be defined at the system level, because this complexity can be hidden within the SPN entity. Our main concern is to define architectures that do not impose any specific solutions. In a heterogeneous 4G system with its different providers (in terms of size, available resources, locality, services, capital, etc.), this is an additional degree of freedom. Different approaches are principally suitable for

management purposes such as proprietary console or Web-based management, SNMP (Case, Fedor, Schoffstall, & Davin, 1990), COPS (Durham et al., 2000), GMPLS, and so forth.

Possible Approaches to 4G

On a high abstraction level, three approaches to 4G are theoretically possible 4G (Varshney & Jain, 2001).

Multimode Devices

Multimode devices (which already exist on the market, e.g., GSM/WiFi phones, PDAs with 802.11 WLAN, Bluetooth and GSM access modules, smartphones with Bluetooth capabilities, etc.) easily expand the effective coverage area managing the cooperation issues by the installed software. This concept pushes the 4G connection management complexity to the terminals, that is, it does not require any additional complexity in the wireless networks. However, the terminal equipment has to integrate operational logics including not only every technology-specific treatment but also the translation of quite different technological parameters to be able to make decisions. It is not clear if this can be done in an economically reasonable fashion for multiple, very different technologies, in particular taking into account the vertical (in the sense of the ISO/OSI model) complexity of QoS, security, and mobility management.

Overlay Networks

Another possibility is the installation of an overlay network of 4G access points situated above the actually available wireless networks. Note that in this approach the devices will still need to have several network interfaces to be able to access the entire infrastructure. The distinction lies in the additional complexity, which is completely shifted to the overlay. The requirements on the underlying technology are minimal. The overlay has to define the necessary signaling and transport functions. Besides the physical access to the used technology, the wireless device has to implement the overlay access module that will implement 4G signaling, 4G management, 4G security, 4G transport, and so forth functions. An example for such architecture would be the well-known All-IP approach discussed in the following sections.

Common Access Protocol

The third possibility is to unify the access protocols of the wireless networks, thus enabling users to access the 4G network by some standard means. This possibility implies separation of the transport and the control planes. Further, it is necessary to identify technology-specific functions that are part of the control plane. These functions have to be externalized and reflected by an abstraction layer/abstraction application program interface (API) that could then implement this common access protocol.

Note that this list is exhaustive (meaning that there are no other possible approaches to an integrated 4G system in the sense of the previous section). However, the mentioned alternative approaches are not necessarily mutually exclusive. It is imaginable to have some combinations of these general high-level approaches in a final solution. In the following, we present some of the proposed 4G architectures classifying these according to the previous scheme.

Related Work

Related Work on 4G Architectures

In Raivio (2001) the author discusses the currently most popular approach to 4G. This approach is based on a common Internet core for different networks, unifying everything over IP and the related Internet Engineering Task Force (IETF) technologies. With respect to this so-called All-IP (sometimes Full-IP) approach, the author briefly discusses the possibilities and the deficiencies in the concerned IETF protocols including the authentication, authorization, and accounting framework (AAA), Mobile IP, IPv6, IPsec, and SIP. The author points out that this approach is straightforward but also problematic in terms of QoS, security, and mobility management.

The presented All-IP idea is the current state of the art approach in the high-level 4G research. In the classification given in the previous section, All-IP represents an overlay network approach. The IP network is used as an overlay that integrates different technologies. IP technologies are used for both control and transport planes. IP base stations are used as access points in that 4G vision.

In Otsu, Okajima, Umeda, and Yamao (2001) the authors research a possible core network design for 4G systems. Describing the current situation of the telecommunications and the predominance of IP-based applications, they give an outlook on estimated traffic in the future generation of wireless systems. Then they discuss possible wireless transmission characteristics in terms of transmission bit rate, spectrum, area coverage, and hierarchical service area and define such network requirements as seamless connections, reduction in the number of control messages, short delay at handover, reduction of cost per bit, service integration based on IP, and movable network support. The network architecture is then defined as a core network (CN) connecting different ANs like a future, yet-to-be-defined 4G-RAN, and already existing WLAN, 3G, and PSTN to the Internet. CN and 4G-RAN are completely IP-based. The terminals have IP-addresses assigned. The CN is directly connected to 4G-RANs and the Internet and uses gateways to connect to the public switched telephone network (PSTN) and 3G. Mobility management is done by using the hierarchical Mobile IPv6 approach. Additionally, the article discusses some issues in the 4G-RAN configuration. In other words, this proposal is an instantiation of the All-IP approach.

Another All-IP proposal is discussed in Yumiba, Imai, and Yabusaki (2001). The recognized requirements here are huge (IP-) multimedia traffic handling, advanced mobility management (MM), diversified radio access support, seamless service, and application service support. The authors then discuss possible solutions for MM and seamless services and name Mobile IP, Cellular IP, and similar techniques. However, they recognize the deficiencies of such systems since they are hardly suited to provide a mobility management of the same quality as is the case in 3G. The authors claim that the networks beyond IMT2000[5] should be much more location-registration oriented and should identify the location registration management as a study topic. For instance, hierarchical or concatenated location registration techniques have to be studied. Then they discuss handover issues distinguishing local handovers and overall network handovers and identify this feature as a further study object.

Trying to provide an infrastructure-independent access to services and applications for highly mobile users, Kellerer, Vögel, and Steinberg (2002) present a solution based on a communication gateway. Originally driven by an automobile environment, the basic idea is to install an intermediate element between the actual user equipment and the serving networks. From the network point of view, such a communication gateway thus resides within the end-system. Including caching and switching units, the gateway provides a general middleware interface to the applications. Thus, this approach pushes the intelligence towards the end-systems, trying to map user requests at their origin to available networks and services. In our classification, this proposal represents the multimode device approach.

Becchetti, Priscoli, Inzerillli, Mähönen, and Muñoz (2001) take a slightly different approach. Mainly dealing with QoS support over different wireless infrastructures, they define a new intermediate layer between the IP and the second layers. This wireless application layer (WAL) then provides a QoS-generic interface for IP featuring uniform guaranteed link reliability and traffic control. The position of WAL in the ISO/OSI model implies a hop-by-hop QoS agreement logic. The details on the modular architecture of WAL, its class and association based QoS provision, Snoop TCP method to avoid congestions in the TCP layer can be found in the paper. In our classification this proposal is an overlay proposal, since WAL instances have to be integrated in the terminals and in the access points. IP is used as a general transport in the All-IP manner, but the technological heterogeneity is hidden within the WAL, which acts as a convergence sub-layer. WAL

instances rely on SNMP to build the necessary decision bases and so forth.

Related Work on 4G Security

The user verification and network access in heterogeneous environments represents one of the major 4G problems. This is discussed later in detail. One of the problems is the access protocol but there are only some open questions concerning the back-end trust architectures and multi-domain, multi-party AAA.

An interesting related work seems to be Zhang et al. (2002). Introducing the concept of a so-called *virtual operator*, the authors describe how an authentication service reachable over the Internet could authenticate its users in a foreign hot spot environment using AAA. As potential virtual operators the authors see ISPs, content providers, cellular operators, or pre-paid card issuers. To reduce the number of necessary trust relationships between potentially numerous hot spot operators and diverse virtual operators, the authors propose a commonly trusted broker entity.

IETF currently works on the protocol for carrying authentication for network access (Forsber, Ohba, Pati, Tschofenig, & Yegin, 2003) in its PANA working group. PANA specifies an architecture very similar to the IEEE 802.1X architecture used in this work for LAN/WLAN access. PANA is link layer agnostic transporting authentication information between the PANA client and PANA authentication agent at higher layers. Since it is principally capable of identifying users, PANA could thus be used as a common access protocol to heterogeneous networks. However, since PANA has to access a higher level element, the L2 mostly remains unprotected. Also, after the (unprotected) L2 establishment, the local PANA client needs to discover its network's pendant, the PANA authentication agent (PAA). This involves discovery broadcasts and round trips. PANA here nicely illustrates the problems inherent to higher layer network access: questionable security, holes in the access controllers, broadcasting in the access phase, and high network access latency.

Besides, PANA does not optimally support mobility: Without additional mechanisms, the authentication has to be completely restarted at the next visited PAA (even within the same network). Such mechanisms could be a L3 (i.e., in the 4G scope typically IP) context transfer protocol that would allow arbitrary context transfers between different PAAs. IETF will shortly publish its context transfer protocol (CTP) specification (Nakhjiri, Perkins, & Koodli, 2004) as an experimental standard. However, the payload formats for CTP have to be specified too.

The work on the public access wireless networks (PAWNs) can be interesting in the 4G scope since it has to practically resolve several problems very similar to the anticipated 4G problems. PAWNs are typically implemented with IEEE 802.11 technology. Since the integrated 802.11 mechanisms are insufficient for almost all typical PAWN areas (per user quality of service, system-wide mobility, security, user network access, etc.), the solutions proposed for PAWNs are typically completely decoupled from the underlying technology. Hence, the practical experiences gained in such installations are of tremendous importance for the 4G research.

An approach for WLAN hot spots providing a secure wireless Internet access in public places is Microsoft's CHOICE (Bahl, Balachandran, & Venkatachary, 2001). The authors build a network that globally authenticates users and then securely connects them to the Internet via a serving 802.11 WLAN. A reasonable argumentation against IPsec for this purpose can be found in the publication. Introducing a new software module (PANS) instead of IPsec, the architecture promises authorization, access control, privacy, security, last hop quality of services, and accounting. However, this software (responsible for packet marking on mobile hosts) has to be installed on all mobile terminals, effectively modifying protocol stacks. The WLAN itself is open but does not allow any connections to any other networks, except for HTTPS connections to the global authenticator (global MS Passport service) and HTTP to the local Web server where, for example, the software module can be downloaded. Network's PANS authorizer module obtains key information from the global authenticator after successful user authentication. The authorizer can also install all required policies.

It then reroutes the traffic to a PANS verifier. The latter actively processes every packet checking the mark/tag added by the PANS module running on the mobile and providing, for example, per user access control and accounting.

Mobility support for public WLANs is presented in Friday et al. (2001). Using a similar packet tagging approach as in CHOICE, the authors describe their GUIDE/GUIDE II systems. Originally meant for a metropolitan scale access using modified client protocol stacks, GUIDE offers ordinary citizens secure and accountable Internet access over the deployed 802.11 WLAN-infrastructure. GUIDE II adds handover management using Mobile IPv6. IPv6 datagrams are tagged by clients using the modified MobileIPv6 stack. Programmable access routers ensure that only packets containing valid access tokens get to the trusted core network. Over an access router, users authenticate at an AAA authentication server. The latter distributes session keys to the access router group and the mobile terminal. User payload encryption is optionally possible between the router and the user equipment.

4G SECURITY REQUIREMENTS

4G security measures have to provide protection for 4G users and 4G providers.

There is no particular and evident reason why 4G security could be easier to achieve than 3G or 2G security. On the contrary, there are several reasons why it could be indeed more difficult, some of which are discussed in the *4G Vulnerabilities* section. One of the obvious reasons is the heterogeneity of the 4G system. Other reasons are provider inequality and the envisioned connection ubiquity.

Main security considerations in our 4G vision refer to the open system interfaces. One of the security targets is thus provider-provider interface. However, the most important and 4G-characteristic target is the user-network interface (including the user-service interface[6]). In the following sections we discuss these topics, specifically dealing with the user-network interface.

Important, but not necessarily new, security provisions must be considered in the internal provider network organization. The latter point is not discussed in the following.

4G Vulnerabilities

Vulnerabilities of Wireless Networks

Wireless networks are generally more vulnerable than their wired equivalents. Wireless security is a difficult problem that has to take into account the vulnerable medium per se (unclear network perimeter, shared medium, naturally broadcast, invisible/virtual network access), performance (security overhead, group communications), limited handset capabilities (human-machine interface, CPU, and memory), battery constraints (sleep management, on/off behavior), and different user services (roaming, mobility, localization). These problems have been discussed in this work per wireless technology in the (Hecker, 2005) per wireless technology.

Heterogeneousness adds a new dimension to this discussion. It multiplies the number of available mechanisms and, from the point of view of attacker, caters to more opportunities to attack the overall system (weakest link). New attack scenarios are conceivable: an attacker could use a weakness within one access network and the systemic interdependencies to gain access to another access network. Terminals can be attacked over several available interfaces at the same time. The services have to be provided over several interfaces, thus resulting in tighter performance constraints and complexity. A typical example is a handover between two different technologies (called *vertical handover*), but the same has to be considered for sleep management (*paging*) and generally for signaling.

Vulnerabilities of Service Provider Networks

A 4G system encompassing different technologies has to support complex management mechanisms (control systems, signaling, etc.), which considerably add to the system complexity and thus represent a major vulnerability per se. This is especially true for a multi-provider and thus multi-authority

environment where a mutual preliminary user-network trust does not necessarily exist and must be established by some means (typically involving management subsystems and signaling before the user identity can be verified).

The serving network protection is one of the critical points to ensure service continuity and investment in new infrastructures. From the secure mobility discussions (such as Mobile IP security), we know that visited networks are often overexposed to resource consumption and denial of service. In our 4G vision, an SPN has to be protected from the users on the user-network interface and from the outer world on its backbone interface(s), including protection from other providers.

User Vulnerabilities

As a wireless user is vulnerable to unauthorized data access, traps/impostors, and desinformation, the user must be protected from abuse by third parties and from the part of the serving SPNs.

Given a rising part of the M2M communications and the wish for infrastructureless communications, the user device is also vulnerable to attacks by other devices involved in the provision of the consumed services (impostors, data modifications, data sniffing, man-in-the-middle) and by devices consuming services provided by the user device (denial of service, abuse).

Connected to multiple interfaces over several providers the device is naturally multi-homed. It is potentially exposed to all attacks over the established connections, including malicious code intrusion (viruses, spyware, and worms).

User vulnerability includes headset vulnerability. A typical 4G headset featuring several active interfaces is naturally exposed to different kinds of attacks, such as attacks on device drivers of the communication interfaces, attacks against the transport and signaling communication stacks, and attacks against all services potentially provided or assisted by the headset itself (e.g., file sharing, localization, auto-update). An important and often forgotten point is device theft. Today, mobile devices are trendy and, having a rich and versatile feature set, can be quite expensive. They have become an important accessory and manufacturers are doing their best to render them more portable and more powerful at the same time. It is obvious that these devices have become an interesting target for thieves. Thus, physical device security is an important but insufficient subject. Mobile handsets can store important personal user data (address books, access codes, professional data, personal medical information). Remote device deactivation, blocking, and erasure seem important future security features.

A 4G user needs a particular protection to ensure his/her anonymity and an offer-consistent and verifiable billing. Without any protection, in an international multi-provider 4G environment, a user can be an easy target for both price fraud (charging wrong prices, charging incorrect usage) and user tracking.

Heterogeneous Security

Current wireless technologies have different security considerations and provide corresponding security definitions in the standards. The latter are naturally dedicated to the respective link layer and thus concentrate on the implementation within the network interface cards, adapters, and so forth. In 4G, different link layer technologies are likely to coexist for the reasons explained in the previous sections. Also, the focus changes: in the personal communications the security focus should be on users, not on network devices.

The problem with the characteristic 4G security is twofold. On the one hand, there are very basic open questions that have to be answered by the ongoing research by weighing practical constraints against the required security level. What is security in 4G if we do not know what 4G looks like, what services it is supposed to provide, and in which environments it is going to operate? The system architecture is crucial for the security considerations. Additionally, we need trust and threat models. What are the capabilities of potential attackers? Which ANs will be used and how? Trust models should correspond to the probable usage scenarios. For instance, if users are not "owned" by providers (Pereira, 2000), how can

trust be established and to whom? With all that, a consistent security policy has to be defined along with the security architecture, identifying technology-independent subjects, objects, relationships, authorizations, threats, and protective measures. This is however difficult and defines a problem known as *heterogeneous security*).

On the other hand, there are practical problems concerning the technical applicability of solutions. The security solutions proposed by the wireless technologies are limited to the identified needs. They are thus different from technology to technology reflecting its expected usage. Very often, they fail to fulfill the security requirements, typically because of conceptual or implementational flaws. But even if their implementation is correct, their scope is naturally wrong: as access security, they aim to provide link security, but ultimately providers need service access security and users need personal data security.

How can the defined security policy for the entire system be applied and enforced to all system entities given that the available solutions are different, potentially flawed, and limited to system parts? For instance, if the security policy identifies link encryption as a necessary confidentiality implementation, how can this be universally activated and with which keys and properties? How can we guarantee an adequate, comparable strength of the different encryption mechanisms? What to do with the technologies that do not provide link encryption? The security policy must consider these cases and provide answers to such questions.

4G Security Layer

The aforementioned practical problems with the 4G security can be avoided if the technology-dependent security measures are not used. Instead, all security measures could be applied in the overlaid technology. However, it is often insecure or at least inefficient to enforce security in the overlay. For example, 2G/3G network providers rely on L2 security measures for network access control, frame integrity and link encryption. While the link encryption is not important for the provider, the access control is primordial for infrastructure protection and revenue guarantees. Moreover, the L2 security measures are often implemented in the network interface hardware. Their design includes power consumption and computational resource considerations. A higher level solution would be implemented in the device control logics, that is, typically software. Given the constraints with the 4G terminals (wireless security processing gap), it would be wise to use the hardwired security solutions in the network adapter. Furthermore, in the OSI logic, multiple links could lie between the user and the used L3 device (router), but only one link is possible between the user and any used L2 device. Thus, the L2 security measures are guaranteed to be implemented in the first network entity (the access device), that is, next to the user, at the very edge of the network. That brings the security as close to the user as possible and thus guarantees physical infrastructure protection. Moreover, it potentially scales better since the access devices are designed to support a fixed number of connections, including the connection properties to be enforced. Another point is that higher level security solutions cannot achieve the same user privacy. For instance, user location privacy is in danger since lower layer addresses (such as world-wide unique MAC addresses) cannot be hidden by higher layer security measures.[7]

For reasons stated previously, we think that L2 security is indispensable in 4G. This is by the way also the most characteristic point of 4G: whatever the 4G vision, everybody seems to agree that 4G will be technology-opportunistic, incorporating different wireless ANs in one system. The network access security is thus one of the major challenges, typical and characteristic for 4G.

NETWORK ACCESS SECURITY

A particular security problem is bound to the user network access. The 4G user has a terminal with multiple network interfaces. The security measures for each interface have been designed according to an initial security analysis during the technology standardization phase. Since the technologies are meant for different purposes, the risks and the defined security functions are likely to be different.

The security mechanisms are definitely different. Thus, every interface has different requirements on credentials in terms of identities, expiration policies, initial trust representation, and so forth. These requirements have to be fulfilled since otherwise the interface could be unusable or the access by the means of this interface impossible. If the user definition in the system is consistent, then the 4G user cannot be expected to use multiple identities: in 4G, every network provider needs to be able to identify any given user correctly, in particular in the different ANs, which the user might be using simultaneously. That is important for the authorizations defined in the security policy. It is equally an important requirement for a consistent billing. Network access can thus be divided into various sub-problems that are treated in more details in following.

Network Selection

In the outlined 4G vision, a free service choice is an important design criterion. To provide that choice, users must be able to collect information on the ANs of all available providers. Most importantly, this is required for the decision of which network the user should connect to. For instance, it cannot be generally assumed that every network is accessible for every user (e.g., because the user's home provider does not have any roaming agreement with the provider of the detected network).

Network selection is a problem since some preliminary network access is necessary prior to authentication, which however should be limited so as not to contradict the security policy. Network selection thus represents a security-usability compromise.

In a dynamic multi-provider multi-technology 4G environment, active exchanges (through signaling, like network discovery) are necessary since the existence of system-wide coherent network identifiers do cannot be relied upon. These identifiers have very different meanings in different technologies. For instance, if a 2G provider wants to deploy a supplementary data service over an 802.11 WLANs, what should be used as a network identifier? There is no regulation on service set identification (SSID) naming in the 802.11 WLANs. Besides, in a dynamic 4G environment with the very different proposed services, over different technologies and with different prices, it is difficult to believe that a network identifier alone is a sufficient base for a reasonable network selection decision.

In a user-centric environment, the network selection decision should be made based on physically available networks and channel qualities, user identity and user service authorizations within the encountered networks, and on offered service prices. Especially price display for a given user appears as one of the critical issues in a multi-provider environment characterized by continuous roaming between several different (big/small, national/local, etc.) providers. Indeed, even in 2G with a typical limitation to a handful of providers per location (2-8), users traveling to foreign countries have been known to feel badly informed about pricing of out- and incoming calls. In 4G with multiple-interface terminals and possibly new business models, several providers can be used at the same time, possibly offering similar services at prices depending on dynamic factors such as current network usage (per-session price determination).

The involvement in such rather complex *pre-authenticated* (Hecker & Labiod, 2004) user-network signaling represents major risks for both network operators (infrastructure intelligence, unpaid resource consumption, denial of service) and users (localization, tracking). Additionally, optimizations are necessary to that recurrent process, which in 4G can be repeated in-session, since it can have an important impact on mobility performance (vertical handover).

User-Network Authentication

A user-network authentication is necessary from network provider's point of view to be able to enforce a reliable access control to its resources and to authorize requested service sessions in its infrastructure or at least a transport (connectivity service) over its infrastructure. It is also required by the user's home provider for authorization and billing.

From the user's point of view, network authentication permits to verify the received network identity information, guarantees access to the correct environment, and thus permits to establish trust to the serving provider. It helps to eliminate impostors and to protect against man-in-the-middle attacks.

After the service information collection, some networks can be eliminated by policy or user wish (e.g., a pre-configuration of the type "never use provider X" or rules like "always choose the cheapest available service", etc.) Now, the user can actually access the required services over available networks. A reliable user-network authentication is required at this moment at latest.

The L2 user-network authentication is a problem in 4G since the logical and technological requirements are very different from technology to technology. We illustrate this on an arbitrary example, comparing UMTS and standard 802.11 security.

UMTS uses an external module (USIM) that hides the actual authentication method from the used device and the visited network. The authenticated logical entities are the USIM and the visited network, represented by the authentication center (AuC). USIM is supposed to grant network access to the device (i.e., also to the user). The USIM is capable of key derivation after a successful authentication.

IEEE 802.11 defines a handshake procedure based on credentials existing between the network (the access point) and the user. The whole procedure (i.e., the authentication method, the exchanges, the cryptographic functions and the success conditions) is hardwired in the network interfaces. The only authenticated entity is the network interface of the user device (i.e., the access point is not authenticated). The authentication does not derive any key material. Moreover, the procedures are almost useless because of several concept errors.

As can be seen, the provided services are very different in terms of capabilities and the achieved security level. However, the purpose of this example is not to blame WLAN security. Today, other security models and methods are available for WLANs (notably the 802.11i introducing a different security model). Nevertheless, this situation exemplifies the normality of a heterogeneous 4G: the security models, the trust presumed relationships, the technical possibilities and the vulnerabilities are very different from technology to technology. The resolution of this problem must not lead per se to security problems. Thus, if the L2 authentication is to be used in the 4G scope, every technology has to fulfill a minimal common requirement set. Otherwise, higher level security has to be used and the associated higher level access controllers have to be collocated with the L2 access devices. If that cannot be guaranteed, this technology should be considered unsuitable for 4G.

From today's perspective, the requirements on the L2 authentication are cryptographic strength, mutuality, and dynamic key material negotiation for the subsequent session protection. The key material negotiation should provide *perfect forward secrecy* (PFS), that is, a successful attack on the produced key material should not give any clues on the long-term secret such as the used credentials. User location privacy should be supported, that is, if possible, any user-specific identifiers should be unreadable for a third party.

Note that we do not formulate any requirements on the authentication logic (how many parties involved and how), used protocols, implementation, method placement, or on the used trust representation. However, authentication methods are generally hard to conceive and represent one of the most vulnerable parts of modern cryptosystems. Due to the flaws typically found in the authentication methods during their lifetime, and given the number of different authentication methods in 4G, we additionally require that the authentication method be easily updateable.

Whatever the actual mechanisms is, it has to correspond to the performance requirements in terms of possible vertical and horizontal mobility. Fast re-authentication (less RTT) and particularly pre-authentication (over the same or a different interface) seem useful in the 4G context.

Data Encryption and Integrity Functions

Different wireless technologies use very different link encryption and data integrity techniques based on different mechanisms. Typically, shared-key mechanisms are used for both link encryption and data integrity. The actually used key is usually derived from the key material established by the authentication function.

Very often proprietary solutions are implemented both for encryption and data integrity. The needs of the used encryption and integrity mechanisms in terms of key properties (format, length, known weak keys, etc.) and the optionally used initialization vectors are very different. The provided security levels are also quite different. Thus, the situation of these functions is similar to the user-network authentication. If some minimum requirements cannot be fulfilled, these have to be replaced (e.g., in the overlay) or the technology could not be used.

Simultaneously, both functions are in use during the whole session. Thus, their power and resource consumption is particularly critical. For that reason, we think that both encryption and integrity functions should be implemented in the associated network adapter (hardwired or in form of hardwired cryptographic bricks connected by the soft-wired firmware definitions). Both functions must use the key material derived during the last authentication session and support rapid re-keying, both periodical and on-demand. Ideally, both functions should be cryptographically strong. However, if flaws are detected, the rapid re-keying can help mitigate the problem by changing the encryption keys very often.

Provider-Provider Security

In 2G/3G providers usually sign preliminary bilateral contracts known as *roaming agreements*. Such agreements build the basis for mutual user authentication, authorization, service and charging. Every provider thus sets up a special subsystem serving AAA requests from other providers, acting as peers. Such requests are as such subject to prudent access control, authorization, and extensive logging.

Principally, that mechanism can also be used in 4G. However, the differences between the provider size and financial weight must be accounted for. In a multi-provider environment, it cannot be reasonably assumed that all providers will still trust each other. Another point is that bilateral agreements are not a scalable approach for a big number of providers ($O(n^2)$).

From the WiFi network experience, we know that instead providers use additional trusted entities as their official roaming contract partner. Such trusted entities are either special brokers or provider associations acting as separate legal bodies. This approach permits to reestablish trust and to minimize the number of bilateral contracts.

To ensure correct billing and charging providers often rely on external billing services and involve third party clearing houses (e.g., financial audit institutions certifying the correctness of the bills and the processes).

Other Security Problems

The remaining security issues mainly concern the SPN, its integrity, and its internal interfaces. Network engineering techniques such as flow and traffic separation, filtering, and continuous monitoring are classically used to achieve a good security level.

This is not an easy problem to solve. However, its exact resolution highly depends on the actually responsible provider: both the security needs and the technical capabilities will change depending on the provider size. That is why, at this moment, we prefer to hide the complexity within the SPN body.

APPROACHES TO 4G SECURITY

In the previous section we defined several requirements on 4G security. 4G systems are still in an early concept phase and specific realizations do not yet exist. However, different approaches are possible to achieve the technology-spanning security mechanisms, often required.

Virtualization

Virtualization is an important means of integrating flexibility in the system design. Virtualization specifies *what* is to be done but not *how* it should be done. In other words, different behaviors accessible and corresponding to the same specified interface can be used (sometimes interchangeably) during the system runtime. The instantiation can happen by pre-configuration, through soft- and firmware updates or even dynamically, at request.

Examples for virtualization include the GSM and UMTS security (GSM 11.11, n.d.; 3rd Generation Partnership Project [3GPP] TS 33.102, n.d.) but also, for example, EAP in IEEE 802.1X (2001) and 802.11i (IEEE Draft, n.d.). The approaches to the virtualization are very different.

2G/3G security relies upon smart cards that represent the network counterparts for authentication and per packet encryption. The actual algorithms and methods are hidden and implemented within the closed card; they are always run against the home provider, who also acts as smart card issuer. In that manner, every home provider has a free choice of standard or better mechanisms to fulfill his/her particular security requirements. The whole transport and signaling infrastructure, including the visited network provider, is independent of that implementation. It is thus feasible to enforce different authentication and per packet security on a per user basis.

The usage of 802.1X/EAP protocol in 802.11i for access control provides a generic authentication function: by specifying how to control, transport, and evaluate user authentication frames instead of specifying how to authenticate users, this standard is now open to authentication method choices. The deployed infrastructure is freed from any authentication logic; only the central authentication server has to implement the actual mechanism, such as, for example, EAP-TLS specifying TLS (Dierks & Allen, 1999) transport over EAP. That enables an authentication method choice on a per-session, per-user basis.

Virtualization is thus a strong design principle for open systems. It thus seems very interesting for 4G security. Nevertheless, even with virtualization, requirements on all mechanisms need to be thoroughly specified.

Adaptation

Adaptation refers to dynamic changes within the implementations of the communicating parties. This could concern the user terminal security measures and the provided network and service environment.

Adaptation could rely on different profiling mechanisms, including machine learning. However, in the telecommunications context, it could also involve more pragmatic signaling-based adaptation. Given the current network situation, the used access network technology and an extensive user-network signaling capable of expressing user needs, the network could actually create a (virtual) SPN corresponding exactly to users' expectations in the chosen access network technology. Different virtualization techniques can be used in that scope, from the previous security virtualization examples to infrastructure virtualization techniques such as VLAN (IEEE 802.1q) or MPLS (Rosen, Viswanathan, & Callon, 2001). This approach could ultimately provide users with their own virtual environments, inaccessible by others, and, at the same time, render the actual physical SPN and its management subsystems inaccessible by the users. Hence, this approach could come handy to solve parts of the problem with the heterogeneity of the ANs.

On the terminal, adaptation can help bridge the differences in the available implementations of the access network security. By inspecting the available (active) interfaces, the really activated measures, and taking into account the available information on recently discovered low level vulnerabilities (user input, secure home network signaling channel, etc.), the terminal implementations could preprocess the sent data, so it still fulfills the overall security policy in spite the insufficiencies.

Standardization

Since the 4G does not yet exist, standardization could be used at these early stages to build a good

base for future 4G security. Basically, such standardization efforts should apply to new definitions and adapt the existing technologies, so these could be used in the future 4G landscape.

In 4G, standardization is one of the central discussions. Not everything can be standard, since otherwise we migrate back from the technology-opportunistic vision to a monolithic one-technology-vision. On the other hand, without any standards, hardly any communication is possible. The compromise between what we standardize in the 4G scope and what we leave to the respective technology is the most critical design decision.

The standardization should respect the three introduced interfaces, differentiating user-network, provider-provider, and internal SPN interfaces (mainly management plane).

Virtualization plays an important role for 4G standardization. We can learn from the former experiences that specifying what and how separately is more flexible. To provide adaptation, we need at least a common signaling standard. This represents a seemingly viable alternative approach to the current pure overlay solutions such as All-IP. We could standardize a common 4G signaling protocol, including virtual definitions for network access and data protection phases, and then use the access technologies *as is*, without any additional changes, as a pure data transport.

CONCLUSION

The 4G reflections started about 2000-2001 are not yet mature enough to present a sound overview of the 4G security. At the current state, there is no common 4G vision and what will eventually be called 4G is an open question.

Independent of that, we believe that the technology-opportunistic system as the one presented in this chapter will eventually be built. That is the reason why the new security problems related to the high system heterogeneity and the new usage scenarios and presented in this chapter seem to be of major importance for the understanding of the vulnerabilities and design of future telecom systems.

More specifically, in this chapter, we present the development process from 1G to 4G discussing telecommunications landscape changes and time scales. We then introduce the current state of the 4G discussion and present our vision of 4G as a technology-opportunistic, user-centric mobile services system built of multi-interface terminals and heterogeneous ANs, bound by a decent management subsystem. Given that 4G shape, conform to the main trend in the current 4G research, we introduce main system interfaces, its links and entities to discuss its vulnerabilities.

We then introduce 4G security requirements, justifying the special character of and insisting on the network access phase. Finally, we propose several high level approaches to 4G security, including virtualization, adaptation and standardization.

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ENDNOTES

1 Since users are the main focus of our work, we prefer this term to the synonymic *operator,* which refers to the infrastructure.

2 This is not limiting since any legal body can have multiple user assignments.

3 This is used consistently to the original definition given in Zhang et al. (2002). However, since in this special case no infrastructure exists, the actually "operated" entity is the user. This term is thus also consistent with our strictly user-oriented view.

4 That underlines the fact that our model mainly requires the service contract as a means for a reliable user identification. Indeed, without any pre-established trust, no reliable billing is possible.

5 International Mobile Telecommunications 2000, ITU's common name for different 3G variants.

6 Note that generally these two problems are not equivalent. However, in our 4G vision we suppose that SPNs are organized as integrated transport and services networks run by the same authority. In that view, the difference between the two is of a very technical nature; it is merely limited to and by the internal SPN organization.

7 Although the lower layer address and the user identity are two completely different identifiers, one initial passive network observation in the proximity of a victim allows an establishment of a direct relationship.

Chapter XIX
Security Architectures for B3G Mobile Networks

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ABSTRACT

The integration of heterogeneous mobile/wireless networks using an IP-based core network materializes the beyond third generation (B3G) mobile networks. Along with a variety of new perspectives, the new network model raises new security concerns, mainly, because of the complexity of the deployed architecture and the heterogeneity of the employed technologies. In this chapter, we examine and analyze the security architectures and the related security protocols, which are employed in B3G networks focusing on their functionality and the supported security services. The objectives of these protocols are to protect the involved parties and the data exchanged among them. To achieve these, they employ mechanisms that provide mutual authentication as well as ensure the confidentiality and integrity of the data transferred over the wireless interface and specific parts of the core network. Finally, based on the analysis of the security mechanisms, we present a comparison of them that aims at highlighting the deployment advantages of each one and classifies the latter in terms of: (1) security, (2) mobility, and (3) reliability.

INTRODUCTION

The evolution and successful deployment of wireless LANs (WLANs) worldwide has yielded a demand to integrate them with third generation (3G) mobile networks. The key goal of this integration is to develop heterogeneous mobile data networks, named as beyond 3G (B3G) networks, capable of supporting ubiquitous computing. Currently, the network architecture (3rd Generation Partnership Project [3GPP] TS 23.234, 2006) that integrates 3G and WLAN specifies two different access scenarios: (1) the *WLAN Direct IP Access* and (2) the *WLAN 3GPP IP Access*. The first scenario provides to a user an IP connection to the public Internet or to an intranet via the WLAN access network

(WLAN-AN), while the second allows a user to connect to packet switch (PS) based services (such as wireless application protocol [WAP], mobile multimedia services [MMS], location-based services [LBS] etc.) or to the public Internet, through the 3G public land mobile network (PLMN).

Along with a variety of new perspectives, the new network model (3G-WLAN) raises new security concerns, mainly, because of the complexity of the deployed architecture and the heterogeneity of the employed technologies. In addition, new security vulnerabilities are emerging, which might be exploited by adversaries to perform malicious actions that result in fraud attacks, inappropriate resource management, and loss of revenue. Thus, the proper design and a comprehensive evaluation of the security mechanisms used in the 3G-WLAN network architecture is of vital importance for the effective integration of the different technologies in a secure manner.

In this chapter we examine and analyze the security architectures and the related security protocols, which are employed in B3G, focusing on their functionality and the supported security services for both WLAN Direct IP Access and 3GPP IP Access scenarios. Each access scenario (i.e., WLAN Direct Access and WLAN 3GPP IP Access) in B3G networks incorporates a specific security architecture, which aims at protecting the involved parties (i.e., the mobile users, the WLAN, and the 3G network) and the data exchanged among them. We elaborate on the various security protocols of the B3G security architectures that provide mutual authentication (i.e., user and network authentication) as well as confidentiality and integrity services to the data transferred over the air interface of the deployed WLANs and specific parts of the core network. Finally, based on the analysis of the two access scenarios and the security architecture that each one employs, we present a comparison of them. This comparison aims at highlighting the deployment advantages of each scenario and classifying them in terms of: (1) security, (2) mobility, and (3) reliability.

The rest of this chapter is organized as follows. The next section outlines the B3G network architectures and presents the WLAN Direct IP Access and the 3GPP IP Access scenarios. The third section elaborates on the B3G security architectures analyzing the related security protocols for each scenario. The fourth section compares the security architectures and consequently, the two access scenarios. Finally, the fifth section contains the conclusions.

BACKGROUND

The B3G Network Architecture

As shown in Figure 1, the B3G network architecture includes three individual networks: (I) the WLAN-AN, (II) the visited 3G PLMN, and (III) the home 3G PLMN. Note that Figure 1 illustrates the architecture for a general case where the WLAN is not directly connected to the user's home 3G PLMN. The WLAN-AN includes the wireless access points (APs), the network access servers (NAS), the authentication, authorization, accounting (AAA) proxy (Laat, Gross, Gommans, Vollbrecht, & Spence, 2000), and the WLAN-access gateway (WLAN-AG). The wireless APs provide connectivity to mobile users and act like AAA clients, which communicate with an AAA proxy via the Diameter (Calhoun, Loughney, Guttman, Zorn, & Arkko, 2003) or the Radius (Rigney, Rubens, Simpson, & Willens, 1997) protocol to convey user subscription and authentication information. The AAA proxy relays AAA information between the WLAN and the home 3G PLMN. The NAS allows only legitimate users to have access to the public Internet, and finally, the WLAN-AG is a gateway to 3G PLMN networks. It is assumed that WLAN is based on the IEEE 802.11 standard (IEEE std 802.11, 1999).

On the other hand, the visited 3G PLMN includes an AAA proxy that forwards AAA information to the AAA server (located in the home 3G PLMN), and a wireless access gateway (WAG), which is a data gateway that routes users' data to the home 3G PLMN. On the other hand, the home 3G PLMN includes the AAA server, the packed data gateway (PDG) and the core network elements

of the universal mobile telecommunications system (UMTS), such as the home subscriber service (HSS) or the home location register (HLR), the Gateway GPRS support node (GGSN) and the Serving GPRS support node (SGSN). The AAA server retrieves authentication information from the HSS/HLR and validates authentication credentials provided by users. The PDG routes user data traffic between a user and an external packet data network, which is selected based on the 3G PS-services requested by the user. The latter identifies these services by means of a WLAN-access point name (W-APN), which represents a reference point to the external IP network that supports the PS services to be accessed by the user.

As mentioned previously, the integrated architecture of B3G networks specifies two different network access scenarios: (1) the WLAN direct IP access and (2) the WLAN 3GPP IP Access. The first scenario provides to a user connection to the public Internet or to an intranet via the WLAN-AN. In this scenario both the user and the network are authenticated to each other using the extensible authentication protocol method for GSM subscriber identity modules (EAP-SIM) (Haverinen & Saloway, 2006) or the Extensible Authentication Protocol-Authentication and Key Agreement (EAP-AKA) (Arkko & Haverinen, 2006) protocol. Moreover, in this scenario, the confidentiality and integrity of users data transferred over the air interface is ensured by the 802.11i security framework (IEEE std 802.11i, 2004). On the other hand, the WLAN 3GPP IP Access scenario allows a WLAN user to connect to the PS services (like WAP, MMS, LBS, etc.) or to the public Internet through the 3G PLMN. In this scenario, the user is authenticated to the 3G PLMN using the EAP-SIM or alternatively the EAP-AKA protocol encapsulated within IKEv2 (Kaufman, 2005) messages. The execution of IKEv2 is also used for the establishment of an

Figure 1. The B3G network architecture

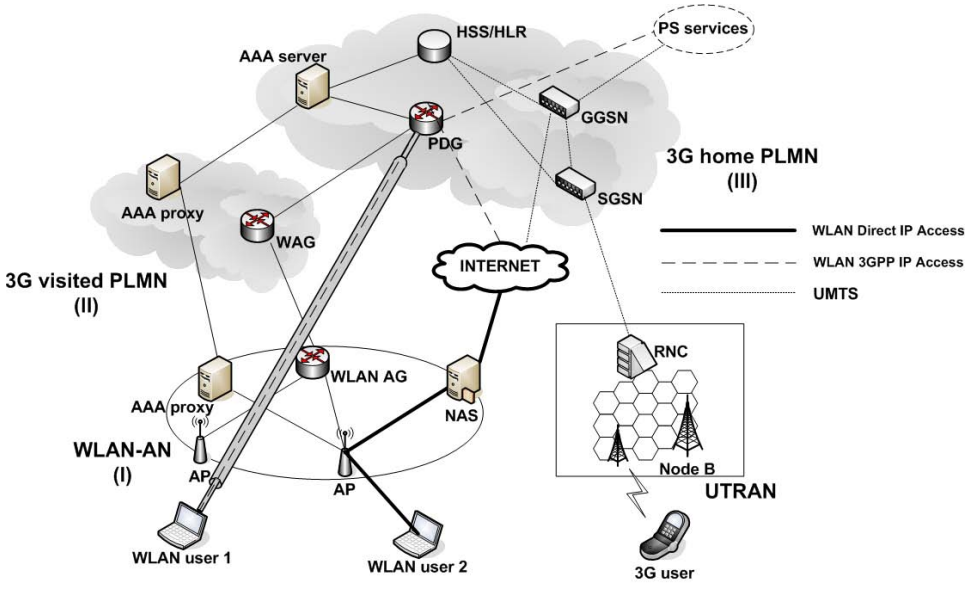


Table 1. 3G-WLAN interworking security mechanisms

Security	*WLAN Direct IP Access*	*3GPP IP Access*
Authentication	EAP-SIM or EAP-AKA	IKEv2 with EAP-SIM or EAP-AKA
Data protection	CCMP or TKIP protocol	IPsec based VPN tunnel using the ESP protocol

CCMP = Counter-Mode/CBC-Mac Protocol TKIP = Temporal Key Integrity Protocol

IP security (Ipsec)-based virtual private network (VPN) (Kent & Atkinson, 1998a) tunnel between the user and the PDG that provides confidentiality and integrity services to the data exchanged between them (see Figure 1). Table 1 summarizes the security protocols employed in each access scenario.

SECURITY ARCHITECTURES FOR B3G NETWORKS

Each network access scenario (i.e., WLAN direct access and WLAN 3GPP IP access) in B3G networks incorporates a specific security architecture, which aims at protecting the involved parties (i.e., the mobile users, the WLAN, and the 3G network) and the data exchanged among them. These architectures (3GPP TS 23.234, 2006) consist of various security protocols that provide mutual authentication (i.e., user and network authentication) as well as confidentiality and integrity services to the data sent over the air interface of the deployed WLANs and specific parts of the core network. In the following, the security architectures and the involved security protocols, which are employed in B3G networks, are presented and analyzed focusing on their functionality and the supported security services.

WLAN Direct IP Access Scenario

In the WLAN Direct IP Access scenario, both the user and the network are authenticated to each other using EAP-SIM or EAP-AKA, which are based on the 802.1X port access control (IEEE std 802.1X, 2001). After a successful authentication, the user obtains an IP address from the WLAN-AN and then, he/she gets access to the public Internet or an intranet, depending on the requested service. In this scenario, the confidentiality and integrity of user's data conveyed over the air interface of WLAN (IEEE std 802.11, 1999) are ensured by 802.11i (IEEE std 802.11i, 2004), which is analyzed next.

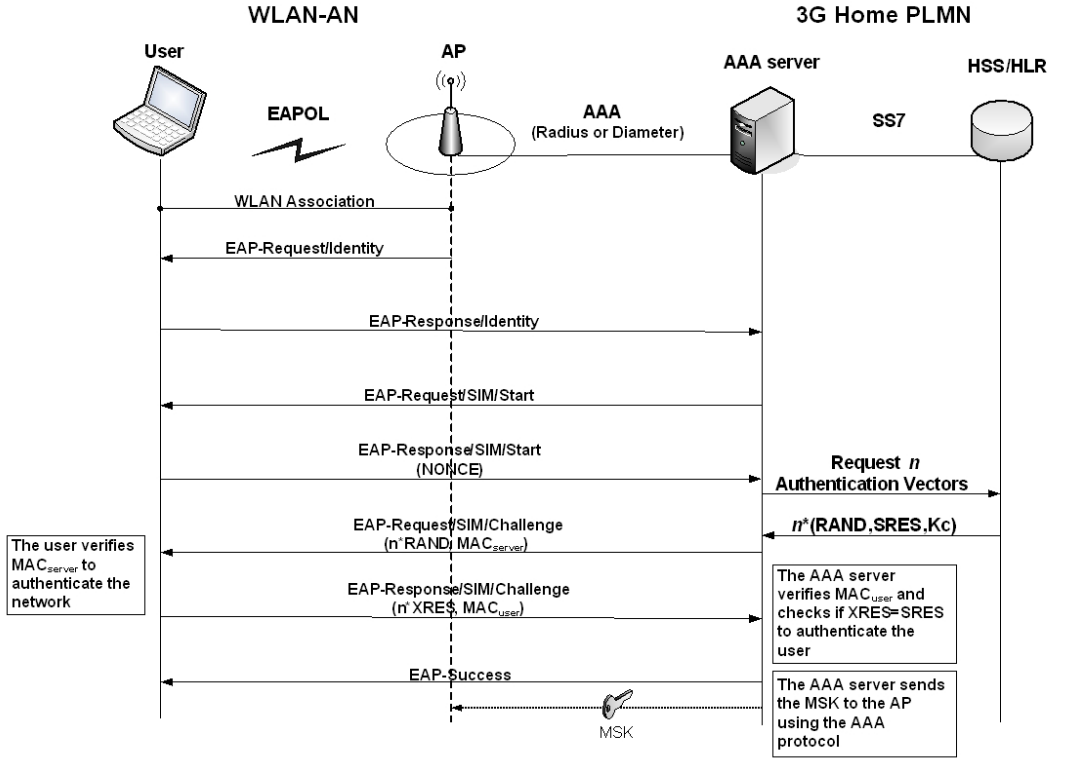
Authentication in WLAN Direct IP Access

The specific security protocol (i.e., EAP-AKA or EAP-SIM) that will be used for mutual authentication between the user and the network depends on the user's subscription. If the user possesses a UMTS subscribers identity module (USIM) card (3GPP TS 22.100, 2001), then, the EAP-AKA protocol is employed. Otherwise, EAP-SIM is used in cases that the user has a SIM-card (European Telecommunications Standards Institute [ETSI] TS 100 922, 1999) of global system for mobile communications (GSM)/general packet radio service (GPRS) (3GPP TS 0.3.6, 2002). When the AAA server receives the user's identity, it fetches from the HSS/HLR the user's profile in order to determine the employed authentication protocol that will be employed (i.e., EAP-SIM or EAP-AKA). In the following, we analyze the functionality of these two protocols focusing on the security services that each one provides.

EAP-SIM. EAP-SIM (Haverinen & Saloway, 2006) provides mutual authentication in a network environment that integrates 3G and WLANs using the credentials included in a SIM-card of a GSM/GPRS subscription. It involves a user, an AAA client (which is actually a wireless AP), and an AAA server that obtains authentication information (i.e., authentication triplets) from the HSS/HLR of the network where the user is subscribed (see Figure 2). EAP-SIM incorporates two basic enhancements that eliminate known security weaknesses of the authentication and key agreement procedure of GSM/GPRS (Haverinen & Saloway, 2006). First, the keys used in EAP-SIM are enhanced to have 128-bits security, in contrast to the 64-bit security of the original GSM/GPRS keys. Second, EAP-SIM supports mutual authentication, in contrast to the GSM/GPRS authentication, which performs only user to network authentication.

For the generation of stronger keys, the EAP-SIM protocol combines n (n=2 or n=3) individual random challenge (RANDs) that result in the derivation of n session keys, Kc. These keys are combined with a random number (NONCE pay-

Figure 2. The EAP-SIM authentication and session key agreement procedure



load), the user identity and other context-related information in order to generate the master key (*MK*) of the EAP-SIM protocol, as shown in the following formula:

*MK= SHA1(Identity| n*Kc| NONCE| Version List| Selected Version)*[1], (1)

where SHA1 is a hash function (Eastlake & Jones, 2001). In the sequel, the produced key *MK* is fed into a pseudo random function (prf) that generates other keys used in EAP-SIM. From these keys the most important are: (1) the master session key (*MSK*), which is used in 802.11i to generate the encryption keys, as described later on, and (2) the *K_auth* key, which is used in EAP-SIM for the generation of keyed message authentication codes (MACs) for authentication purposes.

Figure 2 shows the message exchange of EAP-SIM between the user and the AAA server, which is analyzed next. Note that the user communicates with the wireless AP via the EAP over LAN (EAPOL) protocol (IEEE std 802.1X, 2004).

- First, the user associates with the wireless AP and the latter sends an EAP-Request/Identity message to the user asking for his/her identity.
- The user responds with a message (EAP-Response/Identity) that includes his/her identity in the format of network access identifier (NAI) (Aboba & Beadles, 1999). This identity can be either the International Mobile Subscriber Identity (IMSI), or a temporary identity (i.e., pseudonym).
- Knowing the user's identity, the AAA server issues an EAP-Request/SIM/Start message, which actually starts the authentication procedure.
- The user sends back an EAP-Response/SIM/Start message that includes a nonce parameter

(NONCE), which is the user's challenge to the network.

- Upon receiving this message, the AAA server communicates with HSS/HLR and obtains *n* (*n*=2 or *n*=3) authentication triplets (RAND, SRES, Kc) for the specific user (the holder of the SIM-card). The generation of the GSM authentication triplets is based on a permanent, pre-shared (between the user and the network) secret key, *Ki*, which is assigned to the user when the latter is subscribed to the GSM/GPRS network.
- Then, the AAA server sends to the user an EAP-Request/SIM/Challenge message, which contains the *n* RANDs and the MAC_{server} of the message payload, which is calculated using the *K_auth* key as follows:

$$MAC_{server}=HMAC\_SHA1_{K\_auth}(EAP\text{-}Request/SIM/Challenge(n*RAND)|\ NONCE)^2, \quad (2)$$

where *NONCE* is the nonce sent by the user to the AAA server, and HMAC-SHA1 (Krawczyk, Bellare, & Canetti, 1997) is the MAC algorithm that generates the keyed hash value. Before the calculation of the MAC_{server} value, the AAA server must first generate the *MK* key (see Eq. 1), and, subsequently, the *K_auth* and *MSK* keys.

- Upon receiving the EAP-Request/SIM/Challenge, the user executes the GSM/GPRS authentication algorithms *n* times (one for each received RAND), in order to produce the *n* Kc keys and the *n* expected response (XRES) values. In the sequel, using the produced *n Kc* keys he/she generates the *MK* (see Eq. 1), and, consequently, the *K_auth* and the *MSK* keys, similarly, to the AAA server.
- Next, the user verifies the MAC_{server} using the *K_auth* key, and if this check is successful, then, the network is authenticated to the user, and the latter conveys to the AAA server the generated *n* XRES values within a EAP-Response/SIM/Challenge message. This message also includes the MAC_{user} value generated as follows:

$$MAC_{user}=HMAC\text{-}SHA1_{K\_auth}(EAP\text{-}Response/SIM/Challenge(n*XRES)\ |\ n*XRES)^3, \quad (3)$$

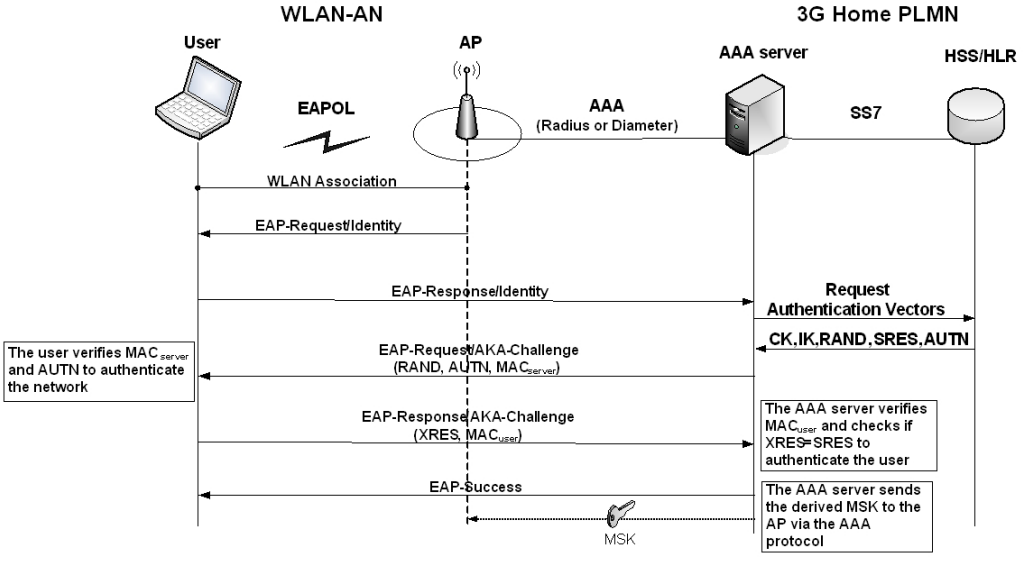
- Upon receiving this message, the AAA server examines whether the produced MAC_{user} is valid and if the *n* XRES values are equal to the *n* SRES values received from HSS/HLR for authentication. If these checks are successful, the AAA server sends an EAP-Success message to the user indicating the successful completion of the authentication procedure. In addition, the AAA server sends to the wireless AP the session key *MSK* within an AAA message (e.g., Radius or Diameter).

At this point, both the user and the network are mutually authenticated, and the user and the wireless AP share the key *MSK*, which is used for encryption purposes in the employed 802.11i security framework (see the *Data protection-802.11i standard* section).

EAP-AKA. EAP-AKA (Arkko & Haverinen, 2006) is an alternative to the EAP-SIM authentication protocol that uses a USIM-card and the UMTS AKA procedure. It involves the same network components with EAP-SIM (i.e., a user, an AAA client and an AAA server) and uses the same protocols for communication between them (i.e., EAPOL, Radius, Diameter, etc.). In the following, the EAP-AKA message exchange is analyzed:

- Likewise EAP-SIM, in the first two messages in the EAP-AKA negotiation (see Figure 3) the wireless AP requests for the user's identity (EAP request/identity message), and the latter replies by sending an EAP response/identity message, which contains his/her permanent IMSI or a temporary identity in an NAI format.
- After obtaining the user's identity, the AAA-server checks whether it possesses a 3G authentication vector, stored from a previous authentication with the specific user. If not, the AAA server sends the users IMSI to the HSS/HLR. The latter generates *n* 3G authentication vectors for the specific user

Figure 3. The EAP-AKA authentication procedure and session key agreement



by using the UMTS permanent secret key, *K*, which is assigned to the user when he/she is subscribed to the network, and sends it to the AAA-server. Note that an authentication vector includes a RAND, the authentication token (AUTN), the XRES, the encryption key (*CK*), and the integrity key (*IK*) (Xenakis & Merakos, 2004).

- In the sequel, the AAA server selects one out of *n* obtained authentication vectors to proceed with the EAP-AKA authentication procedure and stores the remaining *n*-1 for future use. From the selected authentication vector, the AAA server uses the keys *CK* and *IK* and the identity of the user to compute the *MK* of EAP-AKA as shown in the following formula:

$$MK = SHA1(Identity|IK|CK), \quad (4)$$

MK is used as a keying material to generate the *MSK* and the *K_auth* key. The AAA server uses the *K_auth* key to calculate a keyed MAC_{server} (see Eq. 5), which verifies the integrity of the next EAP-AKA message (EAP-Request/AKA-Challenge).

$$MAC_{server} = HMAC\text{-}SHA1_{K\_auth}(EAP\text{-}Request/AKA/Challenge(RAND,AUTN)), \quad (5)$$

- The AAA server sends this message (EAP-Request/AKA-Challenge) to the user that contains the RAND, AUTN, and MAC_{server} payload. After receiving this information message, the user executes the UMTS-AKA algorithms and verifies the AUTN payload (Xenakis & Merakos, 2004). In the sequel, he/she generates the *IK* and *CK* keys and uses these two keys, as shown in Equation 4, to calculate the key *MK*. Subsequently, he/she uses *MK* to calculate the key *MSK* and the key *K_auth*, in order to verify the received MAC_{server} value.
- If these verifications (i.e., AUTN, MAC_{server}) are successful, the user computes the user's response to the challenge, noted as XRES payload, and sends an EAP-Response/AKA-Challenge message to the AAA server that includes the XRES and a new MAC_{user} value, which covers the whole EAP message and it is calculated using the *K_auth* key as follows:

MAC_{user}=HMAC-SHA1$_{K_auth}$(EAP-Response/AKA/Challenge(n*XRES)), (6)

- Upon receiving the EAP-Response/AKA-Challenge message the AAA server verifies the received MAC_{user} value and checks if the received user's response to the challenge (XRES) matches with the response (i.e., SRES) received from the HLR/HSS.
- If all these checks are successful, the AAA server sends an EAP-Success message along with the key *MSK* to the wireless AP. The latter stores the key and forwards the EAP-Success message to the user.

Finalizing the EAP-AKA protocol, both the user and the network have been authenticated to each other, and the user and the wireless AP share the key *MSK*, which is used in the security framework of 802.11i for generating the session encryption keys, as described in the next section.

Data Protection-802.11i Standard

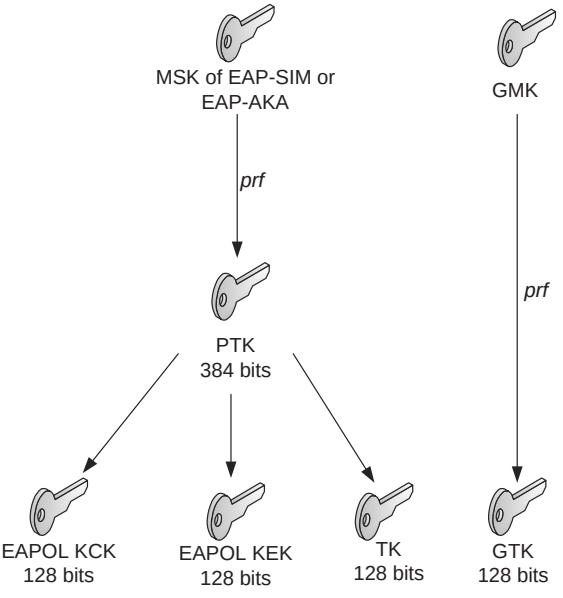
As mentioned previously, 802.11i is employed to provide confidentiality and integrity services to users' data conveyed over the radio interface of the deployed WLAN in the WLAN Direct IP Access scenario. The 802.11i standard was developed to enhance the security services provided in WLANs. Its design was motivated by the fact that the wired equivalent privacy (WEP) protocol, due to its security flaws, could not fulfil the security requirements of WLANs (Borisov, Goldberg, & Wagner, 2001). The design goal of 802.11i is twofold: (1) to provide session key management by specifying a four-way handshake and group key handshake procedures, and (2) to enhance the confidentiality and integrity services provided to users' data by incorporating two security protocols (1) the counter-mode/CBC-MAC protocol (CCMP), which employs the advanced encryption standard (AES), and (2) the temporal key integrity protocol (TKIP), which uses the same encryption (RC4) with the WEP protocol. In the following, we analyze the four-way and group key handshake procedures of 802.11i and we present the functional details of the CCMP protocol. Since the TKIP protocol is considered to be a short term solution and it is merely a software enhancement of WEP, we do not elaborate further on it.

Four-way and group key handshakes. After a successful completion of the authentication procedure of EAP-SIM or EAP-AKA, the user and the AP perform the four-way and group key handshakes of 802.11i (IEEE std 802.11i, 2004) in order to generate the session keys. In the four-way handshake, both the user and the AP derive the pairwise transient key (*PTK*) from the *MSK* key that was generated in EAP-SIM or EAP-AKA to protect the four-way handshake messages and the unicast messages. In addition, the AP delivers to the user a group temporal key (*GTK*), which is used to protect broadcast/multicast messages. The *GTK* key is generated from the group master key (*GMK*), which is stored and maintained in the AP. The group key handshake is executed whenever the AP wants to deliver a new *GTK* key to the connected users. Note that all the messages exchanged during the four-way and the group key handshakes comply with the EAPOL-Key message format (IEEE std 802.1X, 2004).

As its name implies, the 802.11i four-way handshake consists of a total of four EAPOL-Key messages, which are analyzed next. Each of these messages includes key information (key_info payload), such as key identity, key replay counter, and so forth.

- At the beginning of the four-way handshake, the AP sends an EAPOL-Key message to the user that includes the A_{nonce}, which is a random number used as input for the generation of the *PTK* key, as described later on.
- Upon receiving the first EAPOL-Key message, the user generates a new random number called S_{nonce}. Then, he/she calculates the 384-bits *PTK* key using the first 265 bits of the *MSK* key (*MSK* was generated during the authentication procedure of EAP-SIM or EAP-AKA as described in the *Authentication in the WLAN Direct AP Access* section), the

Figure 4. The CCMP protocol key hierarchy



user's address, the AP's address, the S_{nonce} value, and the A_{nonce} value, as follows:

$$PTK=prf(MSK, \text{“}Pairwise\ key\ expansion\text{”}, Min(AP\ address, user's\ address) \mid Max(AP\ address, user's\ address) \mid Min(A_{nonce}, S_{nonce}) \mid Max(A_{nonce}, S_{nonce})), \quad (7)$$

where *prf* is a pseudo random function, "*Pairwise key expansion*" is a set of characters, and, finally, the Min and Max functions provide the minimum and maximum value, respectively, between two inputs. In the sequel, the generated *PTK* key is partitioned to derive three other keys: (1) a 128-bits key confirmation key (*KCK*) that provides integrity services to EAPOL-Key messages, (2) a 128-bits key encryption key (*KEK*) used to encrypt the *GTK* key as described next, and, (3) a 128-bits temporal key (*TK*) used for user's data encryption (see Figure 4).

- After the calculation of these keys, the user forwards to the AP the second EAPOL-Key message (step 2-Figure 5) that includes the S_{nonce}, the user's Robust Security Network Information Element (RSN IE) payload, which denotes the set of authentication and cipher algorithms that the user supports, and a message integrity code (MIC), which is a cryptographic digest used to provide integrity services to the messages of the four-way handshake and it is computed as follows:

$$MIC = HASH_{KCK}(EAPOL\text{-}Key\ message), \quad (8)$$

where $HASH_{KCK}$ denotes a hash function (i.e., HMAC-MD5 or HMAC-SHA-128) that uses the *KCK* key to generate the cryptographic hash value over the second EAPOL-Key message.

- Upon receiving this message, the AP calculates the key *PTK* and the related keys (i.e., *KCK*, *KEK*, and *TK* keys), (the same with the user), and, then, verifies the integrity of the message (producing the MIC value). Next, it generates the 128-bits *GTK* key from the *GMK* key as follows:

$$GTK=prf(GMK, \text{“}Group\ key\ expansion\text{”} \mid AP\ address \mid G_{nonce}), \quad (9)$$

where G_{nonce} is a random number generated from the AP to derive the *GTK* key

- In the sequel, the AP replies to the user by sending the third EAPOL-Key message (step 3), which includes the A_{nonce} value (the same with the first EAPOL-Key message), an MIC over the third EAPOL-Key message, the AP's RSN IE, and the *GTK* key, which is used to protect the broadcast/multicast messages and it is conveyed encrypted using the *KEK* key, as follows:

$$Encrypted\ GTK = ENC_{KEK}(GTK), \quad (10)$$

where ENC_{KEK} denotes the encryption algorithm (i.e., AES or RC4), which uses the *KEK* key to encrypt the *GTK* key.

- By receiving this message, the user checks whether the MIC is valid and compares his/her RSN IE with the AP's RSN IE ensuring that they support the same cryptographic algorithms. If all these checks are correct, the user decrypts the *GTK* key using the *KEK* key and sends to the AP the last message of the four-way handshake (step 4), which includes an MIC payload over the fourth EAPOL-Key message, to acknowledge to the AP that he/she has installed the *PTK* key and the related keys (i.e., *KEK*, *KCK*, and *TK* keys), as well as the *GTK* key.
- Once the AP receives the fourth EAPOL-Key message, it verifies the MIC as previously. If this final check is successful, the four-way handshake is completed successfully, and both the user and the AP share: (1) the *TK* key to encrypt/decrypt unicast messages, and (2) the *GTK* key to encrypt/decrypt broadcast/multicast messages.

In case that the AP wants to provide a new *GTK* key to the connected users, it executes the group key handshake, as shown in Figure 5.

Figure 5. The four-way and group key handshakes of 802.11i

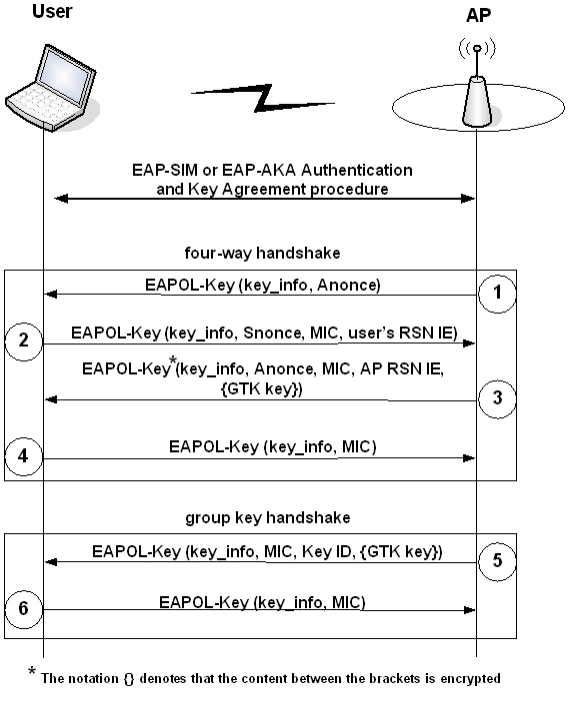
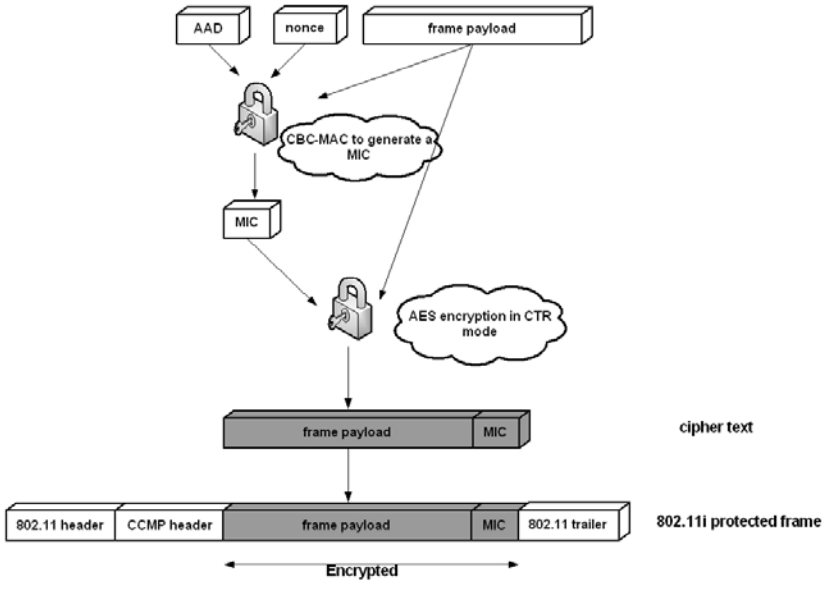


Figure 6. The CCMP protocol



- The AP first generates a fresh *GTK* key from the *GMK* key and sends an EAPOL-Key message that includes an MIC value and the new *GTK* key to the users. Note that MIC is computed over the body of this EAPOL-Key message using the *KCK* key, and the *GTK* key is conveyed encrypted using the *KEK* key. Recall that both the user and the AP share the *KEK* and *KCK* keys, which were generated in the four-way handshake.
- Upon receiving the previous message, the user employs the *KCK* key to verify whether the MIC is valid and then, he/she decrypts the *GTK* key using the *KEK* key. Finally, he/she replies to the AP with an EAPOL-Key message, which includes an MIC that acknowledges to the AP that he/she has installed the *GTK* key.
- Once the AP receives this message, it verifies the MIC. If this final verification is successful, then, the group key handshake is completed successfully and the user can encrypt broadcast/multicast messages using the new *GTK* key.

CCMP Protocol. 802.11i incorporates the CCMP protocol to provide confidentiality and integrity services to users' data conveyed over the radio interface of WLANs. The CCMP protocol combines the AES encryption algorithm in CounTeR mode (CTR-AES) to provide data confidentiality and the Cipher Block Chaining Message Authentication Code (CBC-MAC) protocol to compute an MIC over the transmitted user's data that provides message integrity (Whiting, Housley, & Ferguson, 2003).

The operation of the CCMP protocol can be divided into three distinct phases. In phase 1, the CCMP protocol constructs an additional authentication data (AAD) value from constant fields of the 802.11 frame header (IEEE std 802.11, 1999). In addition, it creates a nonce value from the priority field of the 802.11 frame header and from the packet number (PN) parameter, which is a 48-bit counter incremented for each 802.11i protected frame. In phase 2, the CCMP protocol computes an MIC value over the 802.11 frame header, the AAD, the nonce, and the 802.11 frame payload using the CBC-MAC algorithm and the *TK* key (or the *GTK* key for broadcast/mulitcast

communication). Recall that the *TK* key is part of the *PTK* key that is generated in the four-way handshake. In the sequel, CCMP forms the cipher text of the 802.11 frame payload and the produced MIC, using the CTR-AES encryption algorithm and the *TK* key (or the *GTK* key). Finally, in phase 3, the CCMP protocol constructs the 802.11i frame from the concatenation of: (1) the 802.11 header, (2) the CCMP header, which is created from the PN parameter and the identity of the encryption key, (3) the cipher text, and (4) the 802.11 trailer, which is the frame check sequence (FCS) (see Figure 6). The receiver of the 802.11i frame must verify that the PN parameter is fresh and the MIC value is valid. If these checks are successful, then, the receiver decrypts the 802.11i frame payload using the *TK* key (or the *GTK* key).

WLAN 3GPP IP Access

In contrast to the WLAN Direct IP Access scenario, in which a user gets access to the public Internet, directly, through the WLAN-AN, the WLAN 3GPP IP Access scenario provides to the WLAN user access to the PS services or the Internet through the 3G PLMN. Before getting access to them, the user must perform the six (6) discrete steps, presented in Figure 7 and described as follows:

1. **Initial authentication.** The user and the network are authenticated to each other using either the EAP-SIM or EAP-AKA protocol. This authentication step enables the user to obtain a local IP address, called transport IP address, which is used for access to the WLAN environment and the PDG. Note that this initial authentication can be omitted, if the PDG trusts the WLAN network and its users.

Figure 7. 3GPP IP access authentication procedure

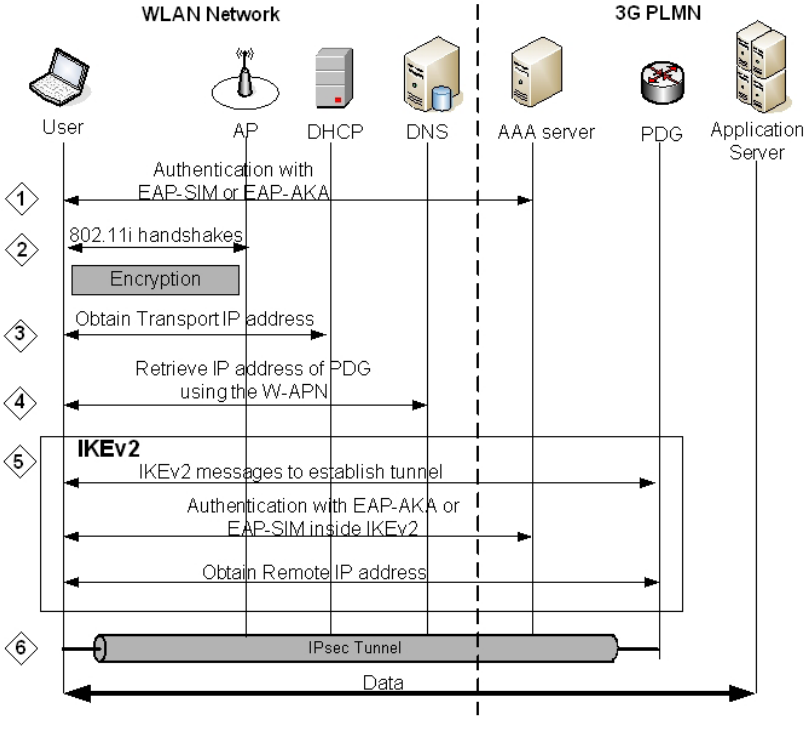
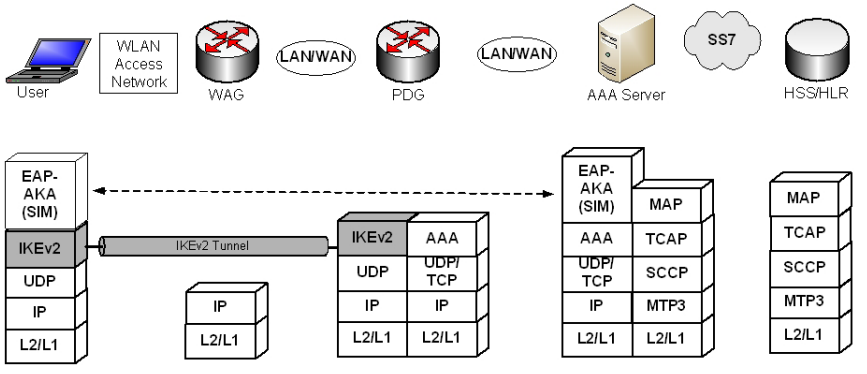


Figure 8. 3GPP IP access authentication protocol stack



2. After the EAP-SIM or EAP-AKA execution, the four-way handshake and optionally the group key handshake follow to provide the 802.11i session keys. Then, the communication between the user and the wireless AP is encrypted using the CCMP or alternatively the TKIP protocol.
3. After the completion of the initial authentication step and the 802.11i handshakes, the user communicates with the Dynamic Host Configuration Protocol (DHCP) server to obtain the transport IP address. This local address is used by the user to execute the IKEv2 in step 4.
4. The user retrieves the IP address of the PDG using the W-APN identity and the domain name system (DNS) protocol. Thus, both the user and the PDG participate in a second authentication step that combines IKEv2 and EAP-SIM or EAP-AKA.
5. **Second authentication.** The user and the PDG execute the IKEv2 negotiation protocol, which encapsulates either EAP-SIM or EAP-AKA for authentication of the negotiating peers. After authentication completion, the user obtains a global IP address, called remote IP address, which is used for access to the PS services and the public Internet via the 3G PLMN. In addition, the execution of IKEv2 results in the establishment of a pair of IPsec security associations (SAs) between the user and the PDG, which are used for the deployment of an IPsec-based VPN.
6. The deployed IPsec based VPN protects user's data exchanged between the user and the PDG (in both directions) ensuring data origin authentication, data confidentiality and message integrity.

Figure 8 presents the protocol stack used in the 3GPP IP Access scenario for each entity that participates in the authentication procedure. The main authentication protocol is EAP-SIM or EAP-AKA, which is executed between the user and the AAA server. The user encapsulates EAP-SIM or EAP-AKA messages within IKEv2 and conveys them to the PDG. The latter acting as an AAA client transfers the EAP-SIM or EAP-AKA messages to the AAA server using an AAA protocol. Note that the AAA protocol can be either RADIUS, which runs over the user datagram protocol (UDP) or Diameter, which runs typically over the TCP protocol. The AAA server also includes the mobile application part (MAP) protocol stack to be able to communicate with the HSS/HLR and obtain authentication triplets and authorization information.

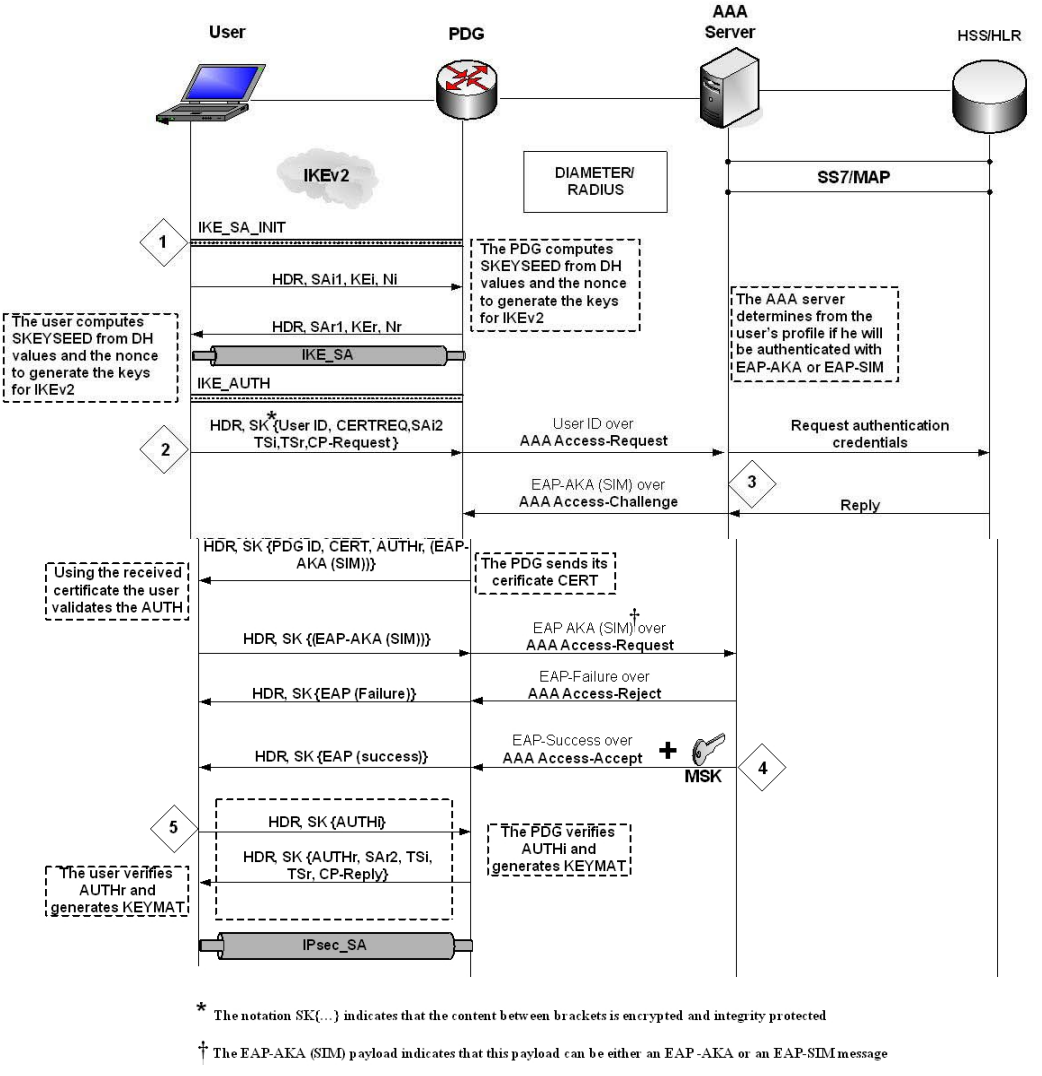
From the previous steps that a user has to perform to get access to the PS services or the public Internet in the WLAN 3GPP IP Access scenario, the initial authentication using either EAP-SIM or EAP-AKA (step 1) and the 802.11i handshakes (step 2) are the same with these of the WLAN Direct IP Access scenario, which has been analyzed in

the *Authentication in the WLAN Direct IP Access* and *Data protection-802.11i standard* sections. Moreover, the acquisition of a local IP address (step 3) and the retrieval of the PDG address (step 4) do not present any significant interest from a security point of view. Thus, in the following sections we analyze the second authentication step (step 5), which includes a combined execution of IKEv2 with EAP-SIM or EAP-AKA, and the deployment of a bidirectional VPN that protects data exchanged.

Authentication in WLAN 3GPP IP Access

IKEv2 (Kaufman, 2005) is a simplified redesign of IKE (Harkins & Carrel, 1998) that allows two peers to authenticate each other (i.e., mutual authentication) and derive keys for secure communication with IPsec. The exchanged messages within IKEv2 are protected ensuring confidentiality and integrity, while the peers are authenticated using certificates, pre-shared keys, or the EAP protocol. In the con-

Figure 9. The execution of IKEv2 based on EAP-SIM or EAP-AKA



* The notation SK{...} indicates that the content between brackets is encrypted and integrity protected

† The EAP-AKA (SIM) payload indicates that this payload can be either an EAP-AKA or an EAP-SIM message

text of WLAN 3GPP IP Access scenario, the user and the PDG execute IKEv2. The authentication of the user is based on EAP-SIM or EAP-AKA, while the authentication of the PDG is based on certificates.

The IKEv2 protocol is executed in two sequential phases (i.e., phase 1 and phase 2). In phase 1, the user and the PDG establish two distinct SAs: (1) a bidirectional IKE_SA that protects the messages of phase 2, and (2) an one-way IPsec_SA that protects user's data. During phase 2, the user and the PDG using the established IKE_SA can securely negotiate a second IPsec_SA that is employed for the establishment of a bidirectional IPsec based VPN tunnel between them.

The IKEv2 phase 1 negotiation between the user and the PDG is executed in two sub-phases: (1) the IKE_SA_INIT, and (2) the IKE_AUTH exchange, as shown in Figure 9. The IKE_SA_INIT exchange (noted as step 1 in Figure 9) consists of a single request and reply messages, which negotiate cryptographic algorithms, exchange nonces, and do a Diffie-Hellman exchange. In the context of this sub-phase, four cryptographic algorithms are negotiated: (1) an encryption algorithm, (2) an integrity protection algorithm, (3) a Diffie-Hellman group, and (4) a prf. The latter prf is employed for the construction of keying material for all of the cryptographic algorithms used. After the execution of the IKE_SA_INIT, an IKE_SA is established that protects the IKE_AUTH exchange. The second sub-phase (i.e., IKE_AUTH) authenticates the previous messages; exchanges identities and certificates; encapsulates EAP-SIM or alternatively EAP-AKA messages; and establishes an IPsec_SA (step 2-5 in Figure 9). All the messages of IKEv2 include a header payload (HDR), which contains a security parameter index (SPI), a version number, and security-related flags. The SPI is a value chosen by the user and the PDG to identify a unique SA. In the following, the IKEv2 negotiation is analyzed:

- At the beginning of the IKEv2 negotiation (step 1 in Figure 9), the user sends to the PDG the SAi1, which denotes the set of cryptographic algorithms for the IKE_SA that he/she supports, the KEi that is the Diffie-Hellman value, and an Ni value that represents the nonce. The nonce (i.e., a random number at least 128 bits) is used as input to the cryptographic functions employed by IKEv2 to ensure liveliness of the keying material and protect against replay attacks.
- The PDG answers with a message that contains its choice from the set of cryptographic algorithms for the IKE SA (SAr1), its value to complete the Diffie-Hellman exchange (KEr) and its nonce (Nr). At this point, both the user and the PDG can calculate the SKEYSEED value as follows:

$$SKEYSEED = prf((Ni \mid Nr), g \wedge ir)^4, \qquad (11)$$

where prf is the pseudo random function negotiated in the previous messages, and g^ir is the shared secret key that derives from the Diffie-Hellman exchange. The SKEYSEED value is used to calculate various secret keys. The most important are: the *SK_d* used for providing the keying material for the IPsec SA; *SK_ei* and *SK_ai* used for encrypting and providing integrity services, respectively, to the IKEv2 messages from the user to the PDG (IKE_SA); and, finally, *SK_er* and *SK_ar* that provide security services in the opposite direction (IKE_SA).

Finalizing the IKE_SA_INIT exchange, the IKE_AUTH exchange can start. It is worth noting that from this point all the payloads of the following IKEv2 messages, excluding the message header (HDR payload), are encrypted and integrity protected using the IKE_SA (see step 2 in Figure 9).

- The IKE_AUTH exchange of messages starts when the user sends to the PDG a message that includes his/her identity (IDi), which could be in an NAI format, the CERTREQ payload (optionally), which is a list of the certificate authorities (CA) whose public keys the user trusts, and the traffic selectors (TSi and TSr), which allow the peers to identify

the packet flows that require processing by IPsec. In addition, in the same message the user must include the Configuration Payload Request (CP-Request), which is used to obtain a remote IP address from the PDG and get access to the 3G-PLMN.

- After receiving this information, the PDG forwards to the AAA server the user identity (IDi) including a parameter, which indicates that the authentication is being performed for VPN (tunnel) establishment. This will facilitate the AAA server to distinguish between authentications for WLAN access and authentications for VPN setup.
- Upon receiving the IDi, the AAA server fetches the user's profile and authentication credentials (GSM triplets if authentication is based on EAP-SIM, or 3G authentication vectors if authentication is based on EAP-AKA) from HSS/HLR (if these are not available in the AAA server in advance).
- Based on the user's profile, the AAA server initiates an EAP-AKA (if the user possesses a USIM card) or an EAP-SIM authentication (if the user possesses a GSM/GPRS SIM card) by sending to the PDG the first message of the related procedure (i.e., EAP-SIM or EAP-AKA) included in a AAA protocol (i.e., Radius or Diameter) (step 3 in Figure 9). Note that since there is no functional difference between the EAP-SIM and the EAP-AKA authentication when these protocols are encapsulated in IKEv2, we present them in a generic way. Thus, we introduce the EAP-AKA (SIM) payload notation (see Figure 9) to indicate that this payload can be an EAP-SIM or an EAP-AKA message.
- Upon receiving the first EAP-AKA (SIM) message, the PDG encapsulate it within an IKEv2 message and forwards the encapsulated message to the user. Except for the EAP-AKA (SIM) payload, this message also includes the PDG's identity, which identifies the provided 3G services (W-APN) (see the *Background* section), the PDG's certificate (CERT), and the AUTHr field. The latter contains signed data used by the user to authenticate the PDG. Similarly to the previous messages, the payload of this IKEv2 message, except for the message header, is encrypted using the IKE_SA.
- Upon receiving the EAP-AKA (SIM) payload, the user verifies the AUTHr field by using the public key of the PDG included in the certificate field (CERT), and answers by sending an EAP-AKA (SIM) response message encapsulated again within an IKEv2 message. From this point, the IKEv2 messages contain only EAP-AKA (SIM) payloads, which are encrypted and integrity protected as described previously.
- The EAP-SIM or EAP-AKA exchange continues, normally, until an EAP-SUCCESS message (or an EAP-FAILURE in case of a failure) is sent from the AAA server to the PDG, which ends the EAP-AKA or the EAP-SIM dialogue. Together with the EAP-SUCCESS message, the key *MSK* is sent from the AAA server to the PDG via the AAA protocol, as shown in Figure 9 (step 4).
- After finishing the EAP-AKA or EAP-SIM dialogue, the last step (step 5) of IKEv2 re-authenticates the peers, in order to establish an IPsec_SA. This authentication step is necessary in order defeat man-in-the-middle attacks, which might take place because the authentication protocol (e.g., EAP-SIM or EAP-AKA) runs inside the secure protocol (e.g., IKEv2). This combination creates a security hole since the initiator and the responder have no way to verify that their peer in the authentication procedure is the entity at the other end of the outer protocol (Asokan, Niemi, & Nyberg, 2002). Thus, in order to prevent possible attacks against IKEv2 (i.e., man-in-the-middle attacks), both the user and the PDG have to calculate the AUTHi and the AUTHr payloads, respectively, using the *MSK* key that was generated from the EAP-SIM or EAP-AKA protocol. Then, both the user and the PDG send each other the AUTHi and AUTHr payloads to achieve a security binding between the inner protocol (EAP-SIM or EAP-AKA) and the outer protocol (IKEv2).

Note that the PDG together with the AUTHr payload sends also its traffic selector payloads (TSi and TSr), the SAr2 payload, which contains the chosen cryptographic suit for the IPsec_SA and the assigned user's remote IP address in the Configuration Payload Reply (CP-REPLY) payload.

After the establishment of the IPsec_SA the keying material (*KEYMAT*) for this SA is calculated as follows:

$$KEYMAT = prf(SK\_d, Ni \mid Nr), \qquad (12)$$

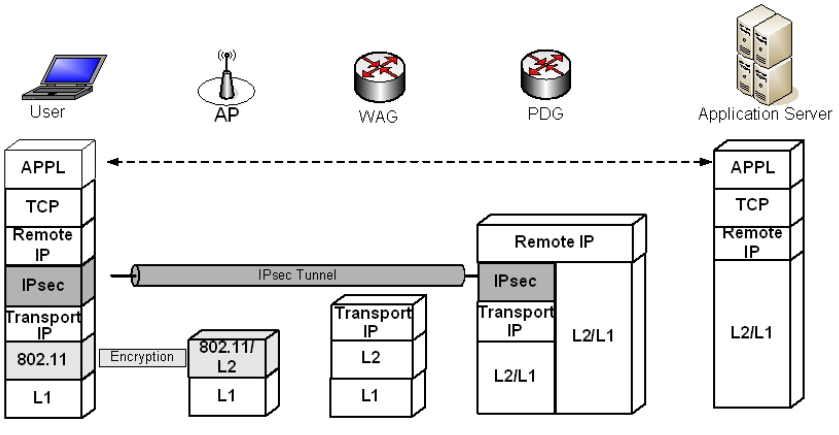
where Ni and Nr are the nonces from the IKE_SA_INIT exchange, and *SK_d* is the key that is calculated from the SKEYSEED value (see eq. 11). The *KEYMAT* is used to extract the keys that the IPsec protocol uses for security purposes. Note that the deployed IPsec_SA protects the one-way communication between the user and the PDG. For bidirectional secure communication, one more SA needs to be established between them (the user and the PDG) by executing the IKEv2 phase 2 over the established IKE_SA.

Data Protection

After the completion of the authentication procedure and the execution of IKEv2 between the PDG and the user, a pair of IPsec_SAs has been established between these two nodes. This pair deploys a bidirectional VPN between them that allows for secure data exchange over the underlying network path. At the same time, the user has been subscribed to the 3G PLMN network for charging and billing purposes using either the EAP-AKA or EAP-SIM protocol.

The deployed VPN runs on top of the wireless link and extends from the user's computer to the PDG, which is located in the user's home 3G PLMN (see Figure 1 and 10). It is based on IPsec (Kent & Atkinson, 1998a), which is a developing standard for providing security at the network layer. IPsec provides two choices of security service through two distinct security protocols: the Authentication Header (AH) protocol (Kent & Atkinson, 1998c), and the encapsulating security payload (ESP) protocol (Kent & Atkinson, 1998b). The AH protocol provides support for connectionless integrity, data origin authentication, and protection against replays, but it does not support confidentiality. The ESP protocol supports confidentiality, connectionless integrity, anti-replay protection, and optional data origin authentication. Both AH and ESP support two modes of operation: transport and tunnel. The transport mode of operation provides end-to-end protection between the communicating end points by encrypting the IP packet payload. The tunnel mode encrypts the entire IP packet (both IP header and payload) and encapsulates the encrypted original IP packet in the payload of a new IP packet.

Figure 10. 3GPP IP access data plane



In the deployed VPN of the WLAN 3GPP IP Access scenario, IPsec employs the ESP protocol and is configured to operate in the tunnel mode. Thus, VPN provides confidentiality, integrity, data origin authentication, and anti-reply protection services protecting the payload and the header of the exchanged IP packets. From the two IP addresses (i.e., transport and remote IP address) of each authenticated user, the remote IP address serves as the inner IP address, which is protected by IPsec, and the transport IP address serves as the IP address of the new packets, which encapsulate the original IP packets and carry them between the user and the PDG (see Figure 10). Thus, an adversary can not disclose, fabricate unnoticed, or perform traffic analysis to the data exchanged between the user and the PDG. Finally, IPsec can use different cryptographic algorithms (i.e., DES, 3DES, AES, etc.) depending on the level of security required by the two peers and the data that they exchange.

COMPARISON OF THE SCENARIOS

Based on the presentation of the two access scenarios (i.e., WLAN Direct IP Access and 3GPP IP Access) that integrate B3G networks and the analysis of the security measures that each one employs, this section provides a brief comparison of them. The comparison aims at highlighting the deployment advantages of each scenario and classifies them in terms of: (1) security, (2) mobility, and (3) reliability.

Regarding the provided security services, both scenarios support mutual authentication. In the WLAN Direct IP Access scenario, the authentication procedure employs either EAP-SIM or EAP-AKA, depending on the user's subscription. However, both protocols present the same security weaknesses, which can be exploited by adversaries to perform several attacks such as identity spoofing, denial of service (DoS) attacks, replay attacks, and so forth (Arkko & Haverinen, 2006; Haverinen & Saloway, 2006). On the other hand, the authentication procedure of the 3GPP IP Access scenario is more secured, since it combines the aforementioned protocols (i.e., EAP-SIM and EAP-AKA) with IKEv2. Specifically, the PDG is authenticated using its certificate, and the user is authenticated using EAP-SIM or EAP-AKA. It is worth noting that since the EAP-SIM and EAP-AKA messages are encapsulated in protected IKEv2 messages, the identified security weaknesses associated with them are eliminated.

Regarding confidentiality and data integrity services, both scenarios protect sensitive data conveyed over the air interface. More specifically, in the WLAN Direct IP Access scenario, high level security services are provided only in cases that the CCMP security protocol is applied, since it incorporates the strong AES encryption algorithm. A downside of applying CCMP is that it requires hardware changes to the wireless APs, which might be replaced. In the WLAN 3GPP IP Access scenario, data encryption is applied at the layer 2 (using WEP, TKIP, or CCMP) and layer 3 (using IPsec), simultaneously (see Figure 10). This duplicate encryption provides advanced security services to the data conveyed over the WLAN radio interface, but at the same time it may cause bandwidth consumption, longer delays, and energy consumption issues at the level of mobile devices.

Another deployment feature, which can be used for comparing the two scenarios, has to do with mobility. The WLAN Direct IP Access scenario may support user mobility by employing one of the mobility protocols, proposed for seamless mobility in wireless networks (Saha, Mukherjee, Misra, & Chakraborty, 2004). On the other hand, in the WLAN 3GPP IP Access scenario, the established VPN between a user and the PDG adds an extra layer of complexity to the associated mobility management protocols of this scenario. This complexity arises from the fact that as the mobile user moves from one access network to another and his/her IP address changes, the mobility protocols must incorporate mechanisms that maintain, dynamically, the established VPN, enabling the notion of mobile VPN. An attempt to address this problem can be found in Dutta et al., 2004) that designs and implements a secure universal mobility architecture, which incorporates standard mobility

management protocols, such as mobile IP for achieving mobile VPN deployment.

Finally, the deployed IPsec-based VPNs between the users and the PDG in the 3GPP IP Access scenario may raise reliability issues. Reliability is perceived as the ability to use VPN services at all times, and it is highly related to the network connectivity and the capacity of the underlying technology to provide VPN services. In the 3GPP IP Access scenario, all data traffic passes through the VPN tunnels that are extend from the users to the PDG. The number of the deployed VPNs can grow significantly, due to the fact that each user can establish multiple VPNs at the same time to access different services. Thus, the PDG must be able to support a large number of simultaneous VPNs in order to provide reliable security services.

CONCLUSION

This chapter has analyzed the security architectures employed in the interworking model that integrates 3G and WLANs, materializing B3G networks. The integrated architecture of B3G networks specifies two different network access scenarios: (1) the WLAN Direct IP Access, and (2) the WLAN 3GPP IP Access. The first scenario provides to a user connection to the public Internet or to an intranet via the WLAN-AN. In this scenario both the user and the network are authenticated to each other using EAP-SIM or EAP-AKA, depending on the user's subscription. Moreover, the confidentiality and integrity of the user's data transferred over the air interface are ensured by the 802.11i security framework. On the other hand, the WLAN 3GPP IP Access scenario allows a user to connect to the PS services (like WAP, MMS, LBS, etc.) or to the public Internet through the 3G PLMN. In this scenario, the user is authenticated to the 3G PLMN using EAP-SIM or alternatively EAP-AKA encapsulated within IKEv2, while the network is authenticated to the user using its certificate. In addition, the execution of IKEv2 is used for the establishment of an IPsec-based VPN between the user and the network that provides extra confidentiality and integrity services to the data exchanged between them.

ACKNOWLEDGMENT

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KEY TERMS

Authentication, Authorization, and Accounting (AAA): AAA is a security framework which provides authentication, authorization, and accounting services. The two most prominent AAA protocols are Radius and Diameter.

Beyond Third Generation (B3G): B3G is the integration of heterogeneous mobile networks through an IP-based common core network.

Counter-Mode/CBC-MAC Protocol (CCMP): CCMP is a security protocol defined in 802.11i, which employs the AES encryption to provide confidentiality and data integrity services.

Extensible Authentication Protocol (EAP): EAP is a security framework used to provide a plethora of authentications options, called EAP methods.

Extensible Authentication Protocol-Authentication and Key Agreement (EAP-AKA): EAP-AKA is an EAP method based on UMTS authentication of USIM cards.

Extensible Authentication Protocol method for GSM Subscriber Identity Modules (EAP-SIM): EAP-SIM is an EAP method based on GSM authentication of SIM cards.

802.11i: 802.11i is a security framework that incorporates the four-way handshake and group-key handshake for session key management and specifies the TKIP and CCMP security protocols to provide confidentiality and integrity services in 802.11 WLAN.

IKEv2: IKEv2 is a security association (SA) negotiation protocol used to establish an IPsec-based VPN tunnel between two entities.

IP security (IPsec): IPsec is a security protocol used to provide VPN services.

ENDNOTES

1 (| means string concatenetation and the notation *n**Kc denotes the *n* Kc keys concatenated)

2 (The notation *n**RAND denotes the *n* RAND values concatenated)

3 (The notation *n**XRES denotes the *n* XRES values concatenated)

4 | means string concatenation

Chapter XX
Security in UMTS 3G Mobile Networks

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ABSTRACT

This chapter analyzes the security architecture designed for the protection of the universal mobile telecommunication system (UMTS). This architecture is built on the security principles of second generation (2G) systems with improvements and enhancements in certain points in order to provide advanced security services. The main objective of the third generation (3G) security architecture is to ensure that all information generated by or relating to a user, as well as the resources and services provided by the serving network and the home environment are adequately protected against misuse or misappropriation. Based on the carried analysis the critical points of the 3G security architecture, which might cause network and service vulnerability are identified. In addition, the current research on the UMTS security and the proposed enhancements that aim at improving the UMTS security architecture are briefly presented and analyzed.

INTRODUCTION

The universal mobile telecommunication system (UMTS) (3rd Generation Partnership Project [3GPP] TS 23.002, 2002) is a realization of third generation (3G) networks, which intend to establish a single integrated system that supports a wide spectrum of operating environments. Users have seamless access to a wide range of new telecommunication services, such as high data rate transmission for high-speed Internet/intranet applications, independently of their location. Thus, mobile networks comprise a natural extension of the wired Internet computing world, enabling access for mobile users to multimedia services that already exist for non-mobile users and fixed networking.

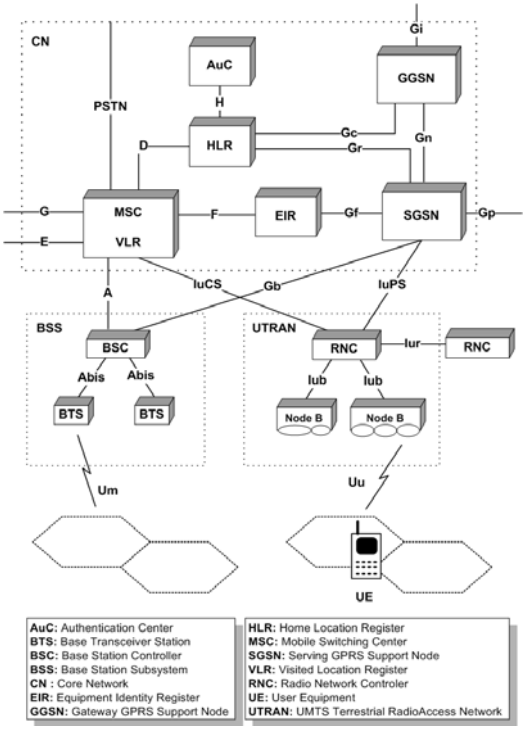
Along with the variety of new perspectives, UMTS also raises new concerns on security issues. Wireless access is inherently less secure and

mobility implies higher security risks compared to those encountered in fixed networks. The advanced wireless and wired network infrastructure, which supports higher access rates, and the complex network topologies, which enable "anywhere-anytime" connectivity, may increase the number and the ferocity of potential attacks. Furthermore, the potential intruders are able to launch malicious attacks from mobile devices with enhanced processing capabilities, which are difficult to trace. To defeat the possible vulnerable points, UMTS has incorporated a specific security architecture named as 3G security architecture.

This chapter analyzes the security architecture designed for the protection of UMTS. This architecture is built on the security principles of second generation (2G) systems with improvements and enhancements in certain points in order to provide advanced security services. The main objective of the 3G security architecture is to ensure that all information generated by or relating to a user, as well as the resources and services provided by the serving network (SN) and the home environment (HE) are adequately protected against misuse or misappropriation. Based on the carried analysis the critical points of the 3G security architecture, which might cause network and service vulnerability are identified. In addition, the current research on the UMTS security and the proposed enhancements that aim at improving the UMTS security architecture are briefly presented and analyzed.

The rest of this chapter is organized as follows. The next section outlines the UMTS network architecture and the 3G security architecture. The third section elaborates on the network access security features, and the fourth section examines the network domain security. The fifth section presents the user domain security, the application domain security, the visibility of security operation and configurability, and the network-wide confidentiality option. The sixth section analyzes potential weaknesses concerning the 3G security architecture and the seventh section presents the current research on the UMTS security. Finally, the last section contains the conclusions.

Figure 1. UMTS network architecture



BACKGROUND

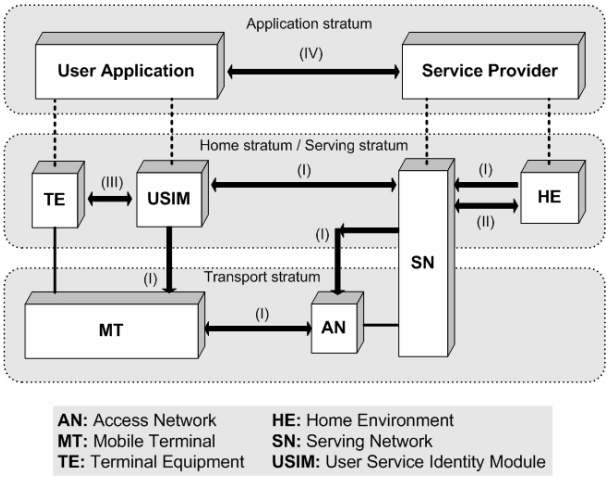
UMTS Network

UMTS has been standardized in several releases, starting from Release 1999 (R99), and moving forward to Release 4 (Rel-4), Release 5 (Rel-5), Release 6 (Rel-6), supporting compatibility with the evolved global system for mobile communications (GSM)/general packet radio service (GPRS) network. The UMTS network architecture includes the core network (CN), the radio access network, and the user equipment, as can be seen in Figure 1. This division provides the necessary flexibility by allowing the coexistence of different access techniques and different core network technologies, thus facilitating the migration form 2G to 3G networks. The fundamental difference between GSM/GPRS and UMTS R99 is that the latter supports higher bit rates (up to 2Mbps). This is achieved through a new wideband code division multiple access (WCDMA) radio interface for the land-based communications system, named UMTS terrestrial radio access network (UTRAN) (3GPP TS 25.401, 2002). UTRAN consists of two distinct elements, Node B, and the radio network controller (RNC). Node B converts the data flows between the lu-b and Uu interfaces and participates in radio resource management. The RNC owns and controls the radio resources of the Nodes B connected to it. The user equipment, which mainly comprises a mobile station (MS) with limited processing, memory, and power capabilities is connected to the UTRAN through the Uu radio interface (3GPP TS 23.002, 2002). The CN of the UMTS R99 uses the network elements of GSM/GPRS such as the home location register (HLR), the visitor location register (VLR), the authentication centre (AuC), the equipment identity register (EIR), the mobile service switching centre (MSC), the Serving GPRS support node (SGSN) and the Gateway GPRS support node (GGSN) (3GPP TS 23.002, 2002).

UMTS Security Architecture

3G security is built on the security principles of 2G systems, with improvements and enhancements in certain points in order to provide advanced security services. The elementary security features employed in 2G, such as subscriber authentication, radio interface encryption, and subscriber identity confidentiality are retained and enhanced where needed. The main objective of 3G security is to ensure that all information generated by or relating to a user, as well as the resources and services provided by the SN and the HE are adequately protected against misuse or misappropriation. The level of protection is better than that provided in

Figure 2. 3G-security Architecture



the contemporary fixed and mobile networks. The security features have been adequately standardized in order to ensure worldwide availability, interoperability, and roaming between different SNs. Furthermore, 3G security features and mechanisms can be extended and enhanced as required by new threats and services (Xenakis & Merakos, 2004b).

Figure 2 gives an overview of the 3G security architecture, illustrating five major security classes (3GPP TS 33.102, 2002):

- Network access security (I)
- Network domain security (II)
- User domain security (III)
- Application domain security (IV)
- Visibility and configurability of security (V)

NETWORK ACCESS SECURITY

Network access security is a key component in the 3G security architecture. This class deals with the set of security mechanisms that provide users with secure access to 3G services, as well as protect against attacks on the radio interface. Such mechanisms include: (1) user identity confidentiality, (2) authentication and key agreement, (3) data confidentiality, and (4) integrity protection of signaling messages. Network access security takes place independently in each service domain.

User Identity Confidentiality

User identity confidentiality allows the identification of a user on the radio access link by means of a temporary mobile subscriber identity (TMSI). This implies that confidentiality of the user identity is protected almost always against passive eavesdroppers. Initial registration is an exceptional case where a temporary identity cannot be used, since the network does not yet know the permanent identity of the user.

The allocated temporary identity is transferred to the user once the encryption is turned on. A TMSI in the circuit switched (CS) domain or P-TMSI in the packet switched (PS) domain has a local significance only in the location area or the routing area, in which the user is registered. The association between the permanent and temporary user identities is stored in the VLR or the SGSN (VLR/SGSN). If the mobile user arrives into a new area, then the association between the permanent and the temporary identity can be fetched from the old location or routing area. If the address of the old area is not known or the connection cannot be established, then, the permanent identity must be requested from the mobile user.

To avoid user traceability, which may lead to the compromise of user identity confidentiality as well as to user location tracking, the user should not be identified for a long period by means of the same temporary identity. Additionally, any signaling or user data that might reveal the user's identity are ciphered on the radio access link.

Authentication and Key Agreement

Authentication and key agreement mechanism achieves mutual authentication between the mobile user and the SN showing knowledge of a secret key (K), as well derives ciphering and integrity keys. The authentication method is composed of a challenge/response protocol (see Figure 3) and was chosen in such a way as to achieve maximum compatibility with the GSM/GPRS security architecture facilitating the migration from GSM/GPRS to UMTS. Furthermore, the user service identity module (USIM) (3GPP TS 22.100, 2001) and the HE keep track of counters SQN_{MS} and SQN_{HE}, respectively, to support the network authentication. The sequence number SQN_{HE} is an individual counter for each user, while the SQN_{MS} denotes the highest sequence number that the USIM has accepted. Whenever the SQN_{HE} is not in the correct range, the mobile station decides that a synchronization failure has occurred in the HE and consequently initiates a resynchronization to the HE.

Upon receipt of a request from the VLR/SGSN, the HE authentication center (HE/AuC) forwards an ordered array of authentication vectors (AV) to the VLR/SGSN. Each AV, which is used in the authentication and key agreement procedure

Figure 3. 3G authentication and key agreement

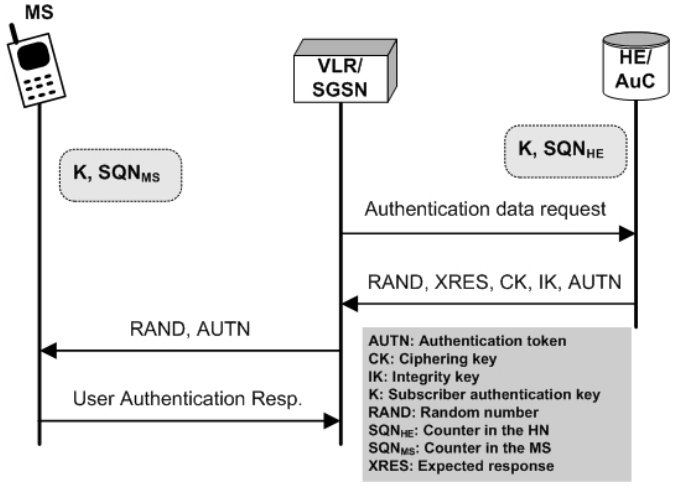
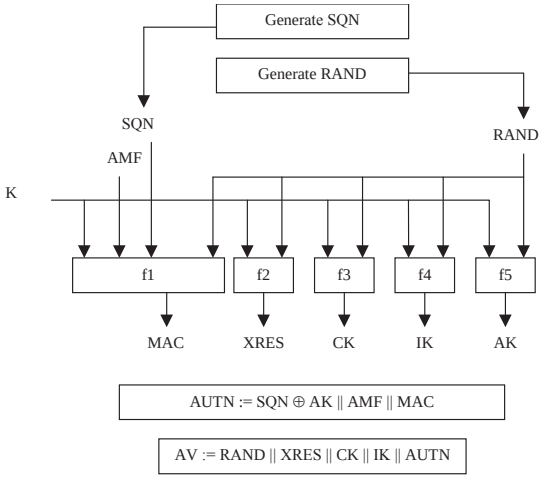


Figure 4. Generation of authentication vectors



between the VLR/SGSN and the USIM consists of a random number (RAND), an expected response (XRES), a cipher key (CK), an integrity key (IK), and an authentication token (AUTN).

Figure 4 shows an AV generation by the HE/AuC. The HE/AuC starts with generating a fresh sequence number (SQN), which proves to the user that the generated AV has not been used before and an unpredictable challenge RAND. Then, using the secret key (K) it computes:

- The Message Authentication Code *(MAC) = f1k (SQN ||[1] RAND || AMF),* where f1 is a message authentication function and the authentication and key management field (AMF) is used to fine tune the performance or bring a mew authentication key stored in the USIM into use.
- The expected response *XRES = f2k (RAND)* where f2 is a (possibly truncated) message authentication function.
- The cipher key *CK = f3k (RAND),*

- the integrity key *IK = f4k (RAND),*
- and the anonymity key *AK = f5k (RAND)* where f3, f4, and f5 are key generating functions.
- Finally, the HE/AuC assembles the authentication token *AUTN = SQN* $\oplus^2$ *AK || AMF || MAC*

It has to be noted that the authentication and key generation functions f1, f2, f3, f4, and f5, and the consequent AV computation follow the one-way property. This means that if the output is known there exists no efficient algorithm to deduce any input that would produce the output. Although the f1-f5 functions are based on the same basic algorithm, they differ from each other in a fundamental way in order to be impossible to deduce any information about the output of one function from the output of the others. Since they are used in the AuC and in the USIM, which are controlled by the home operator, the selection of the algorithms (f1-f5) is in principal operator specific. However, an example algorithm set has been proposed called MILENAGE (3GPP TS 35.205, 2001).

When the VLR/SGSN initiates an authentication and key agreement procedure, it selects the next AV from the ordered array and forwards the parameters RAND and AUTN to the user. The USIM using also the secret key (K) computes the AK,

AK = f5k (RAND),

and retrieves the SQN,

SQN = (SQN $\oplus$ *AK)* $\oplus$ *AK.*

Then, it computes *XMAC = f1k (SQN || RAND || AMF)* and checks whether the received AUTN and the retrieved SQN values were indeed generated in AuC (3GPP TS 33.102, 2002). If so, the USIM computes the user response to the challange *RES= f2k (RAND),* and triggers the mobile station (MS) to send back a user authentication response. Afterwards, the USIM computes the CK,

CK = f3k (RAND),

and the IK,

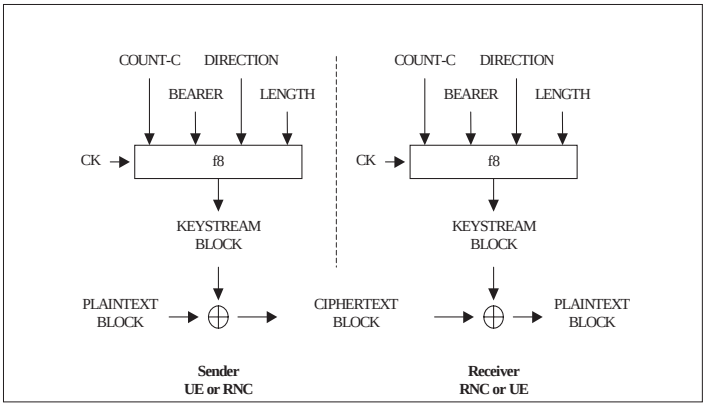
IK = f4k (RAND).

The VLR/SGSN compares the received RES with the XRES field of the AV. If they match, it considers that the authentication and key agreement exchange has been successfully completed. Finally, the USIM and the VLR/SGSN transfer the established encryption and integrity protection keys (CK and IK) to the mobile equipment and the RNC that perform ciphering and integrity functions.

Data Confidentiality

Once the user and the network have authenticated each other, they may begin secure communication. As described previously, a cipher key is shared between the core network and the terminal after a successful authentication event. User and signaling data sent over the radio interface are subject to ciphering using the function (f8). The encryption/decryption process takes place in the MS and the

Figure 5. Ciphering over the radio access link



RNC on the network side. The f8 is a symmetric synchronous stream cipher algorithm that is used to encrypt frames of variable length. The main input to the f8 is a 128-bit secret cipher key CK. Additional inputs, which are used to ensure that two frames are encrypted using different keystreams are a 32-bit value COUNT, a 5-bit value BEARER, and a 1-bit value DIRECTION (see Figure 5). The output is a sequence of bits (the "keystream") of the same length as the frame. The frame is encrypted by XORing the data with the keystream. For UMTS R99, f8 is based on the Kasumi algorithm (3GPP TR 33.908, 2000).

Integrity Protection of Signaling Messages

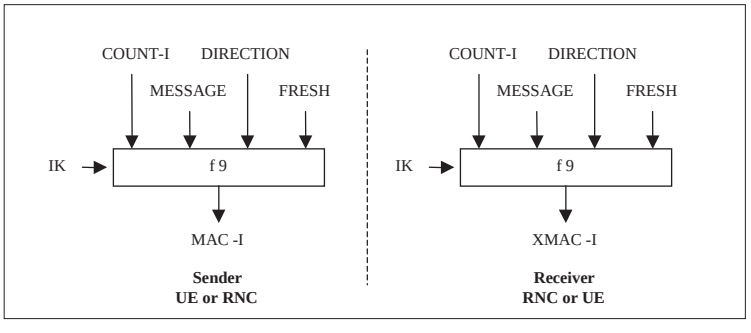
The radio interface in 3G mobile systems has also been designed to support integrity protection on the signaling channels. This enables the receiving entity to be able to verify that the signaling data have not been modified in an unauthorized way since they were sent. Furthermore, it ensures that the origin of the received signaling data is indeed the one claimed. The integrity protection mechanism is not applied for the user plane due to performance reasons.

The function (f9) is used to authenticate the integrity and the origin of signaling data between the MS and the RNC in UMTS. It computes a 32-bit MAC (see Figure 6), which is appended to the frame and is checked by the receiver. The main inputs to the algorithm are a 128-bit secret IK and the variable-length frame content MESSAGE. Additional inputs, which are used to ensure that MACs for two frames with identical content are different, are a 32-bit value COUNT, a 32-bit value FRESH, and an 1-bit value DIRECTION. In the UMTS R99, the f9 is based on the Kasumi algorithm (3GPP TR 33.908, 2000).

NETWORK DOMAIN SECURITY

Network domain security (NDS) features ensure that signaling exchanges within the UMTS core as well as in the whole wireline network are protected. Various protocols and interfaces are used for the control plane signaling inside, and between core networks, such as the mobile application part (MAP) and the GPRS tunneling protocol (GTP) protocols, and the Iu (IuPS, IuCS) and Iur interfaces (3GPP TS 23.002, 2002). These will be protected by standard procedures based on the existing cryptographic techniques. Specifically, the IP-based protocols shall be protected at network level by means of IP security (IPsec) (Kent & Atkinson, 1998), while the realization of protection for the signaling system 7 (SS7)-based protocols and the lu and Iur interfaces shall be accomplished at the application layer. In the following, the NDS context for IP-based (3GPP TS 33.210, 2002) and SS7-based (3GPP TS 33.200, 2002) protocols is presented. Moreover, the employment of traditional security technologies, originally designed for fixed networking, such as firewalls and static virtual private networks (VPNs) are examined. The application of these technologies safeguards the UMTS core network from external attacks and protects users' data when are conveyed over the public Internet.

Figure 6. Derivation of MAC on a signaling message



IP-Based Protocol

The UMTS network domain control plane is sectioned into security domains, which typically coincide with the operator borders. Security gateways (SEGs) are entities at the borders of the IP security domains used for securing native IP-based protocols. It is noted that NDS does not extend to the user plane, which means that packet flows over the Gi (3GPP TS 23.002, 2002) interface will not be protected by the SEGs. The key management functionality is logically separate from the SEG. Key administration centers (KACs) negotiate the IPsec security associations (SAs) by using the Internet key exchange (IKE) protocol (Harkins & Carrel, 1998) in a client mode, on behalf of the network entities (NEs) and the SEGs. The KACs also distribute SAs parameters to the NEs or the SEGs through standard interfaces. In Figure 7 the UMTS NDS architecture for IP-based protocols is depicted.

To secure the IP traffic between two NEs, either a hop-by-hop or an end-to-end scheme may be applied. The first requires that the originating NE establishes an IPsec tunnel to the appropriate SEG in the same security domain and forwards the data to it. The SEG terminates this tunnel and sends the data through another IPsec tunnel to the receiving network. The second tunnel is terminated by the SEG in the receiving domain, which in turn uses IPsec to pass the data to its final destination (path (a) in Figure 7). The end-to-end scheme implies that an IPsec SA is established between the two NEs (path (b) in Figure 7). This scheme can also be applied in case the two parties belong to the same security domain.

Node authentication can be accomplished using either pre-shared symmetric keys or public keys (Harkins & Carrel, 1998). Using pre-shared symmetric keys means that the KACs or the NEs do not have to perform public key operations as well as there is no need for establishing a public key infrastructure. The IPsec is configured either in transport mode or in tunnel mode (Kent & Atkinson, 1998). Whenever at least one end point is a gateway then the tunnel mode suits better. Finally, the IPsec protocol shall always be encapsulation security payload (ESP) (Kent & Atkinson, 1998), given that it can provide confidentiality and integrity protection as well.

SS7-Based Protocols

NDS for SS7-based protocols is mainly found at the application layer. Specifically, in case that the transport relies on SS7 or on a combination of SS7 and IP, then security shall be provided at the application layer. On the other hand, whenever the

Figure 7. NDS architecture for IP-based protocols

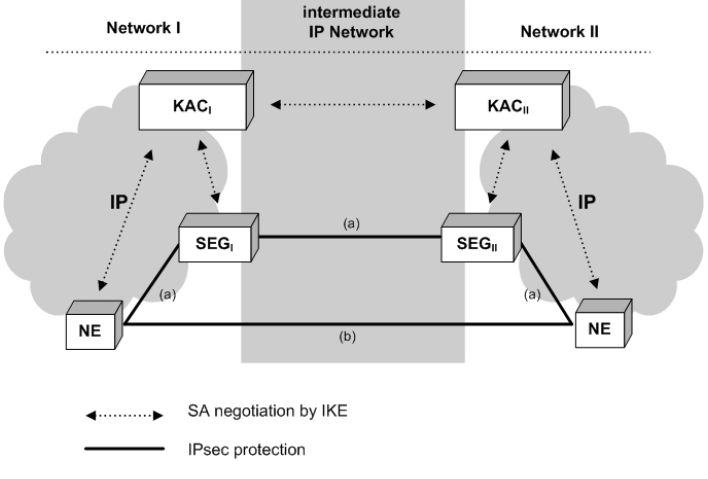
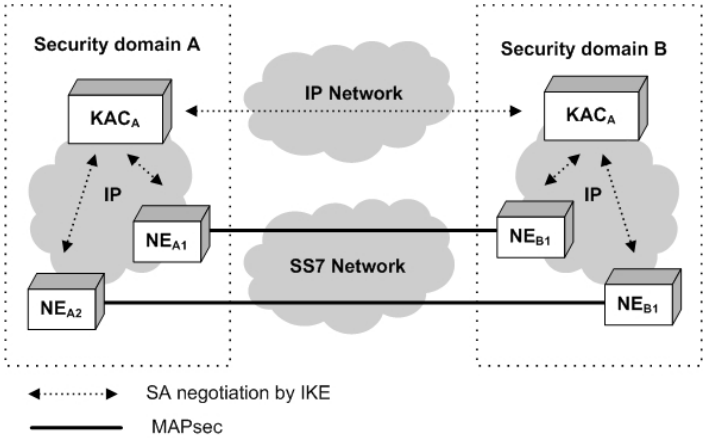


Figure 8. NDS architecture for SS7 and mixed SS7/IP-based protocols



transport is based only on IP, then security may be provided either at the network layer exclusively using IPsec or in a combination of the application and network layer. For signaling protection at the application layer the necessary SAs will be network-wide and they are negotiated by KAC similarly to the IP-based architecture (see Figure 8). End-to-end protected signaling will be indistinguishable to unprotected signaling traffic to all parties, except for the sending and receiving sides.

It is worth noting that in Rel-4 the only protocol that is to be protected is the MAP. The complete set of enhancements and extensions that facilitate the MAP security is termed MAPsec (3GPP TS 33.200, 2002). The MAPsec covers the security management procedures, as well as the security of the transport protocol including data integrity, data origin authentication, anti-reply protection, and confidentiality. Finally, for IKE adaptation a specific Domain of Interpretation is required.

Traditional Network Security Features

Besides the security features that are included in the 3G security architecture, the mobile network operators can apply traditional security technologies used in terrestrial networking to safeguard the UMTS core network as well as the inter-network communications. User data in the UMTS backbone network are conveyed in clear-text exposing them to various external threats. Moreover, inter-network communications are based on the public Internet, which enables IP spoofing to any malicious third party who gets access to it. In order to defeat these vulnerable points, the mobile operators can use two complementary technologies: firewalls and VPNs (Gleeson, Lin, Heinanen, Armitage, & Malis, 2000).

Firewalls can be characterized as a technology providing a set of mechanisms to enforce a security policy on data from and to a corporate network. They are established at the borders of the core network allowing traffic originating from specific foreign IP addresses. Thus, firewalls protect the UMTS backbone from unauthorized penetration. Furthermore, application firewalls prevent direct access through the use of proxies for services, which analyze application commands, perform authentication, and keeps logs.

Since firewalls do not provide privacy and confidentiality, VPNs have to complement them to protect data in transit. VPN establishes a secure tunnel between two points, encapsulates and encrypts data, and authenticates and authorizes user access of the corporate resources on the network. Thus, they extend dedicated connections between remote branches or remote access to mobile users, over a shared infrastructure. Implementing a VPN makes security issues such as confidentiality, integrity, and authentication paramount. There is a

two-fold benefit that arises from VPN deployment: the low cost and security.

The border gateway is an element that resides at the border of the UMTS core network and provides the appropriate level of security policy (e.g., firewall), as well as maintaining static pre-configured security tunnels (e.g., IPsec tunnels) granting VPN services to specific peers. It serves as a gateway between the PS domain and an external IP network that is used to provide connectivity with other PS domains located in other core networks.

USER AND APPLICATION DOMAIN SECURITY FEATURES

User Domain Security

User domain security (3GPP TS 33.102, 2002) ensures secure access to the MS. It is based on a physical device called UMTS integrated circuit card (UICC), which can be easily inserted and removed from terminal equipment, containing security applications such as the USIM (3GPP TS 22.100, 2001). The USIM represents and identifies a user and his/her association to an HE. It is responsible for performing subscriber and network authentication, as well as key agreement when 3G services are accessed. It may also contain a copy of the user's profile.

The USIM access is restricted to an authorized user or to a number of authorized users. To accomplish this feature, the user and the USIM must share a secret (e.g., a PIN). The user gets access to the USIM only if he/she proves knowledge of the secret. Furthermore, access to a terminal or to other user equipment can be restricted to an authorized USIM. To this end, the USIM and the terminal must also share a secret. If a USIM fails to prove its knowledge of the secret then access to the terminal is denied.

Application Domain Security

Application domain security (3GPP TS 33.102, 2002) deals with secure messaging between the MS and the SN or the SP over the network with a level of security chosen by the network operator or the application provider. A remote application should authenticate a user before allowing him/her to utilize the application services and it could also provide for application-level data confidentiality. Application-level security mechanisms are needed because the lower layers' functionality may not guarantee end-to-end security provision. The lack of end-to-end security could be envisioned when for instance the remote party is accessible through the Internet.

USIM application toolkit (3GPP TS 33.111, 2001) provides the capability for operators or third party providers to create applications that are resident on the USIM. To assure secure transactions between the MS and the SN or the service provider (SP), a number of basic security mechanisms such as entity authentication, message authentication, replay detection, sequence integrity, confidentiality assurance, and proof of receipt have been specified and integrated in the USIM Application Toolkit.

Figure 9a. WAP 1.2.1 architecture

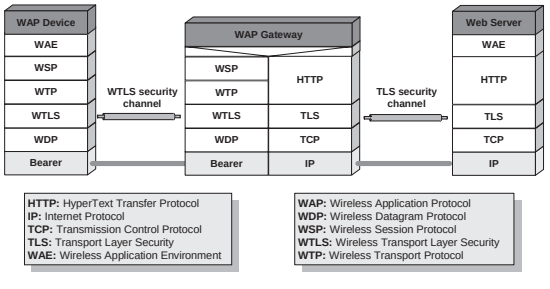
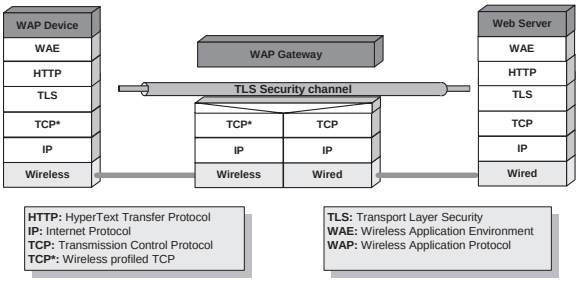


Figure 9b. WAP 2.0 architecture



Wireless Application Protocol (WAP) is a suite of standards for delivery and presentation of Internet services on wireless terminals, taking into account the limited bandwidth of mobile networks as well as the limited processing capabilities of mobile devices. It separates the network in two domains (i.e., the wireless and the Internet domain) and introduces a WAP gateway that translates the protocols used in each domain. The WAP architecture has been standardized in two releases (ver. 1.2.1 and ver. 2.0) (Wireless Application Forum, n.d.).

In WAP 1.2.1 (see Figure 9a), security is applied by using the wireless transport layer security (WTLS) protocol (wireless application forum, n.d.) over the wireless domain and the transport layer security (TLS) protocol over the Internet domain. WTLS, which is based on TLS, provides peers authentication, data integrity, data privacy, and protection against denial-of-service in an optimized way for use over narrow-band communication channels. However, WAP 1.2.1 does not support end-to-end security, since the conveyed data are protected by two separate security channels (i.e., WTLS security channel and TLS security channel).

On the other hand, WAP 2.0 (see Figure 9b) introduces the Internet protocol stack into the WAP environment. It allows a range of different gateways, which enable conversion between the two protocol stacks anywhere from the top to the bottom of the stack. A TCP-level gateway allows for two versions of TCP, one for the wired and another for the wireless network domain. On the top of the TCP layer, TLS can establish a secure channel all the way from the MS to the remote server. Thus, the availability of a wireless profile for TLS enables end-to-end security allowing interoperability for secure transactions.

Security Visibility and Configurability

Although the security measures provided by the SN should be transparent to the end user, visibility of the security operations as well as the supported security features should be provided. This may include: (1) indication of access network encryption; (2) indication of network wide encryption; and (3) indication of the level of security (e.g., when a user moves from 3G to 2G).

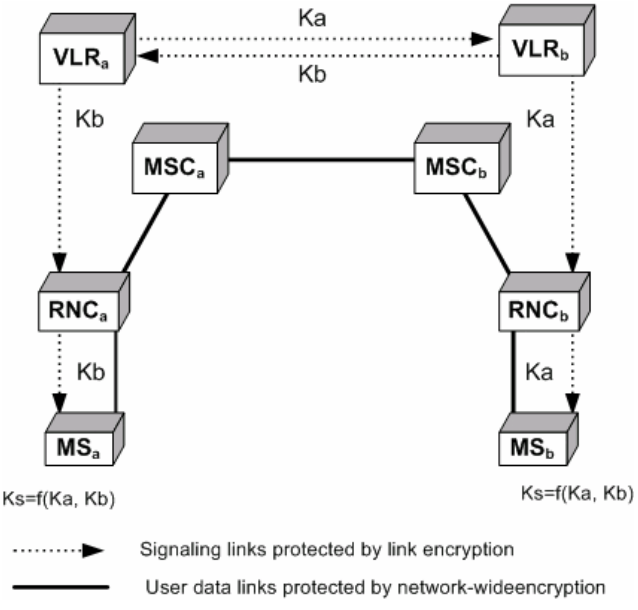
Configurability enables the mobile user and the HE to configure whether a service provision should depend on the activation of certain security features. A service can only be used when all the relevant security features are in operation. The configurability features that are suggested include: (1) enabling/disabling user-USIM authentication for certain services; (2) accepting/rejecting incoming non-ciphered calls; (3) setting up or not setting up non-ciphered calls; and (4) accepting/rejecting the use of certain ciphering algorithms.

Network-Wide User Data Confidentiality

Network-wide confidentiality is an option that provides a protected mode of transmission of user data across the entire network. It protects data against eavesdropping on every link within the network and not only on the vulnerable radio links. Whenever network-wide confidentiality is applied, access link confidentiality on user data between the MS and the RNC is disabled to avoid replication. However, access link confidentiality for signaling information as well as user identity confidentiality are retained to facilitate the establishment of the encryption process. In Figure 10, the network-wide encryption deployment is depicted.

Network-wide confidentiality uses a synchronous stream cipher algorithm similar to that employed in the access link encryption. Initially, a data channel is established between the communicating peers indicating also the intention for network-wide encryption. VLRa and VLRb exchange cipher keys (Ka and Kb) for users a and b, respectively, using cross boundaries signaling protection, and then, pass them to the MSs over protected signaling channels. When each MS has received the other party's key, the end-to-end session key, Ks, is calculated as a function of Ka and Kb. Alternatively, VLRs can mutually agree on the Ks using an appropriate key agreement protocol. Both key management schemes satisfy the lawful interception requirement, since Ks can be generated by the VLRs.

Figure 10. Network-wide encryption deployment



SECURITY WEAKNESSES

The analyzed 3G security architecture provides advanced security services and addresses many of the security concerns that have been listed in the context of next generation mobile networks. However, there are some critical points that need further elaboration and improvements. In the following, the identified security weaknesses of the 3G security architecture, which might cause network and service vulnerability, are briefly presented.

As mentioned previously, the mobile user identity and location is valuable information that requires protection. A possible weakness in the 3G security architecture is the backup procedure for TMSI reallocation (3GPP TS 24.008, 2002). Specifically, whenever the SN/VLR cannot associate the TMSI with the international mobile subscribers identity (IMSI) because of TMSI corruption or database failure, the VLR should request the user to identify himself by means of IMSI on the radio path. Furthermore, when the user roams and the new SN/VLRn cannot contact the previous (old) VLRo or cannot retrieve the user identity; the SN/VLRn should also request the user to identify himself by means of IMSI on the radio path (3GPP TS 33.102, 2002). This may lead an active attacker to pretend to be a new SN to which the user has to reveal his/her permanent identity. In both cases, the IMSI that represents the permanent user identity is conveyed in clear-text on the radio interface, violating user identity confidentiality.

Another critical point is that the users may be identified by means of the IMSI in signaling conversations in the wireline path. For example, the SN/VLR may use the IMSI to request the authentication data for a single user from his/her HE. Thus, user identity confidentiality and user location privacy rely on the security of the wireline signaling connections. NDS features protect signaling exchange in the wireline network architecture with IP and SS7 technologies, but these features are considered for the later versions of the UMTS standardization process, leaving the first one (R99) unprotected.

The authentication and key agreement procedure of UMTS presents two critical security flaws presented in Zhang and Fang (2005). The first one allows an adversary to redirect user traffic from one network to another. This can be achieved because the user (i.e., using the sequence numbers, SQN) can only verify whether an authentication vector

was generated by the HE. On the other hand, he/she cannot determine if an authentication vector was requested by the SN, since the authentication vector could have been requested by any SN. Thus, the adversary owing a false base/mobile station device (i.e., a device that emulates a base station and a mobile station) can impersonate as a genuine base station and entices a legitimate user to camp on the radio channels of the false base station. The adversary can also impersonate as a legitimate mobile station and establishes connection with a genuine base station. This fact allows the adversary to relay messages in between a legitimate mobile station and a genuine base station realizing the redirection attack. This attack represents a real threat since the security levels provided by different networks are not always the same. In addition, it could cause billing problems as the service rates offered by different networks are not always the same, either.

The second security flaw that is related to the UMTS authentication (Zhang & Fang, 2005) allows an adversary to use the authentication vectors corrupted from one network to impersonate other networks. When a network is corrupted, an adversary could forge an authentication data request from the corrupted network to obtain authentication vectors for any user, independent of the actual location of the user. Then, the adversary could use the obtained authentication vectors to impersonate uncorrupted networks and to mount false base station attack against legitimate users. Therefore, the corruption of one network may jeopardize the entire system. For this reason, it is critical that security measures are in place in every network.

The application of firewalls in 3G systems presents some weaknesses since they were originally conceived to address security issues for fixed networks. Firewalls attempt to protect the clear-text transmitted data in the UMTS backbone from external attacks, but they are inadequate against attacks that originate from other mobile network malicious subscribers, as well as from network operator personnel or any other third party that gets access to the UMTS core network. Mobility may imply roaming between networks and operators possibly changing the source address, which because of the static configuration of firewalls may potentially lead to discontinuity of service connectivity for the mobile user. Moreover, the firewalls security value is limited because they allow direct connection to ports and cannot distinguish services.

Similarly to firewalls, the VPN technology fails to provide the necessary flexibility required by typical mobile users. Currently, VPNs for UMTS subscribers are established in a static manner between the border gateway of a UMTS network and a remote security gateway of a corporate private network. This fact allows the realization of VPNs only between a security gateway of a large organization and a mobile operator, when a considerable amount of traffic requires protection. Thus, this scheme can provide VPN services neither to individual mobile users that may require on demand VPN establishment, nor to enterprise users that may roam internationally. In addition, static VPNs have to be reconfigured every time the VPN topology or VPN parameters change.

On the other hand, if a mobile user uses the WAP architecture (ver. 1.2.1), data privacy is not guaranteed. Although encryption is used, the WAP gateway constitutes a security hole since inside the gateway data are transmitted un-encrypted. WTLS is only used between the mobile device and the gateway, while TLS can be used between the gateway and the Web server. From a security point of view, the gateway should be considered as an entity-in-the-middle. This means that data exchanged may be available to people with privileged access to the WAP gateway and thus, the privacy of the data depends on the gateway's internal security policy.

WAP 2.0 does address the "gap" in security caused by protocol translation at the WAP gateway of the previous version (ver. 1.2.1). However, the mobile phone would have to use an IP protocol stack at the expense of larger latency and bandwidth consumption. Although TLS can be used to secure the communication of any application, it must be integrated into the application and thus, to a large extent it is used for Web-based applications. Interaction with the end user is needed, for example, to check with whom a secure session has

been established or to explicitly request the client to authenticate with the server. TLS is generally a resource consuming protocol for deployment in mobile devices with limited processing capabilities and low bandwidth/high latency wireless networks. Moreover, the operation overhead may be increased by complex key-exchange procedures in case the protected service contains cross-references to other services.

Finally, the network-wide encryption may also encounter problems when transcoding is used. Voice calls may need to be transcoded when they cross network borders, meaning that voice data may have to undergo change such as bit-rate change or some other transformation. It is not possible to apply such transformation on an encrypted signal, which implies that the signal has to be decrypted before transcoding. Furthermore, the network-wide confidentiality lacks flexibility and it is not applicable to all types of service in different mobile scenarios. Specifically, it is limited to protecting the communication between mobile subscribers.

CURRENT RESEARCH ON UMTS SECURITY

The weak points of the UMTS security architecture may lead to compromises of end users and network security of the UMTS system. These compromises may influence the system deployment and the users' trend to utilize UMTS for the provision of advanced multimedia services, which realizes the concept of mobile Internet. In the following, the current research on the UMTS security and the proposed enhancements that aim at improving the UMTS security architecture are briefly presented and analyzed.

Identity Confidentiality

To limit the exposure of the permanent identities (IMSI) of mobile users over the vulnerable radio interface, the additional usage of two complementary temporary identities for each mobile subscriber that is attached to the network has been proposed (Xenakis & Merakos, 2004b). One of these temporary identities will reside at the SN ($TMSI_{ALT}$), and the second one at the home network of the mobile user ($TMSI_{HE}$). When the VLR of the SN fail to page a mobile user using the current TMSI, it can try to page him/her using the alternative temporary identity ($TMSI_{ALT}$), which also resides in the VLR. In case of a VLR database failure or a corruption of the temporary identities (i.e., TMSI and $TMSI_{ALT}$) that resides in the VLR, the VLR requests the temporary identity (i.e., $TMSI_{HE}$) from the home network by which it can page the mobile user. This identity resides in the user's home network in order to avoid a possible corruption after a database (VLR) failure. In case that none of the TMSI is valid or all of them are corrupted, the user is not attached to the network.

Both the additional temporary identities (i.e., $TMSI_{ALT}$ and $TMSI_{HE}$) derive from the current TMSI. The latter consists of four octets and its generation procedure is chosen by the mobile operator. However, some general guidelines are applied in all implementations in order to avoid double allocation of TMSIs, after a restart of the allocating node (i.e., VLR or SGSN). For this reason, some part of the TMSI may be related to the time when it was allocated or contained a bit field, which is changed when the allocating node has recovered from the restart. After the generation of a TMSI, the allocating node applies two individual hash functions (i.e., $HASH_{ALT}$ and $HASH_{HE}$), which produce the corresponding $TMSI_{ALT}$ and $TMSI_{HE}$, respectively. Then, the allocating node forwards the three temporary identities to the involved mobile user and the $TMSI_{HE}$ to its home network. In cases that the home and the SN are the same, the $TMSI_{HE}$ can be stored in HLR, which is not affected by the reasons that corrupt the other two temporary identities. Finally, each time that the current TMSI is renewed, the two additional temporary identities change in order to eliminate the possibility of an adversary to link them to the permanent user's identity.

Authentication and Key Agreement

To address the security issues involved with the authentication and key agreement procedure Zhang

and Fang (2005) have proposed an adaptive protocol for mobile authentication and key agreement, called AP-AKA. The proposed protocol can defeat the redirection attack and may drastically lower the impact of network corruption. An overview of AP-AKA is shown in Figure 11.

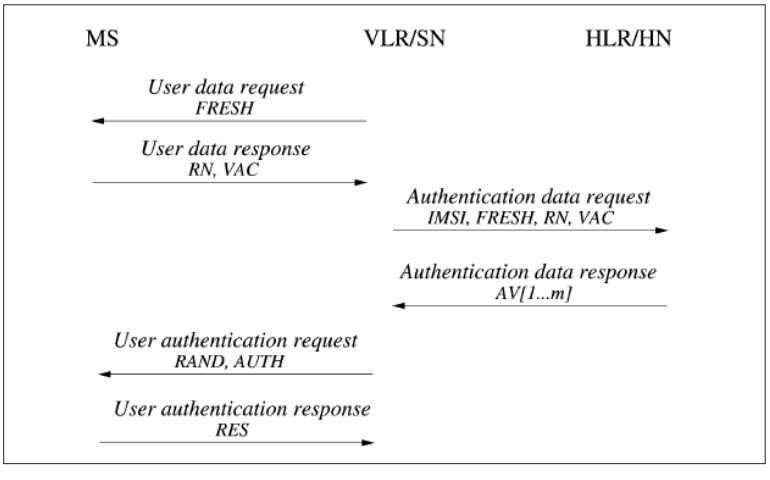
The AP-AKA protocol retains the framework of the legacy authentication and key agreement, but eliminates the synchronization required between the mobile station and its home network (i.e., SQN_{MS} and SQN_{HE}). In AP-AKA, each mobile station and its home network share an authentication key K and three cryptographic algorithms F, G, and H, where F and H are MACs and G is a key generation function. In practice, the authentication key is usually generated by the home network and programmed into the mobile station during service provisioning. Unlike the legacy authentication and key agreement, the home network in AP-AKA does not maintain a dynamic state, for example, the counter, for each individual subscriber. The mobile station can verify whether an AV was indeed requested by a SN and was not used before by the SN. The AP-AKA protocol specifies a sequence of six flows. Each flow defines a message type and format sent or received by an entity. Depending on the execution environment, entities have the flexibility of adaptively selecting flows for execution, and thus the AP-AKA is called an adaptive protocol.

User Data Security

Another weakness of the current UMTS security architecture that can be overcome is related to the lack of effective protection of user data in the fixed part of the UMTS network. To address this problem, two alternative security solutions, which are based on existing security technologies, can be used: (1) the application layer security, and (2) the establishment of mobile VPNs, dynamically, that satisfy users' needs.

Application layer security solutions integrate security into applications at the level of end users. The most prominent protocol that provides security at this layer for the Internet technology is the Secure Sockets Layer (SSL) protocol (Gupta & Gupta, 2001). SSL supports server authentication using certificates, data confidentiality, and message integrity. Since SSL is relatively "heavy" for implementations on mobile devices, which are characterized by limited processing capabilities, a lightweight version of SSL named "KiloByte" SSL (KSSL) has been proposed (Gupta & Gupta, 2001). This SSL implementation (KSSL) provides an advantage by enabling mobile devices (UMTS MS) to communicate directly and securely with a considerable number of Internet Web servers that support SSL.

Figure 11. Overview of AP-AKA

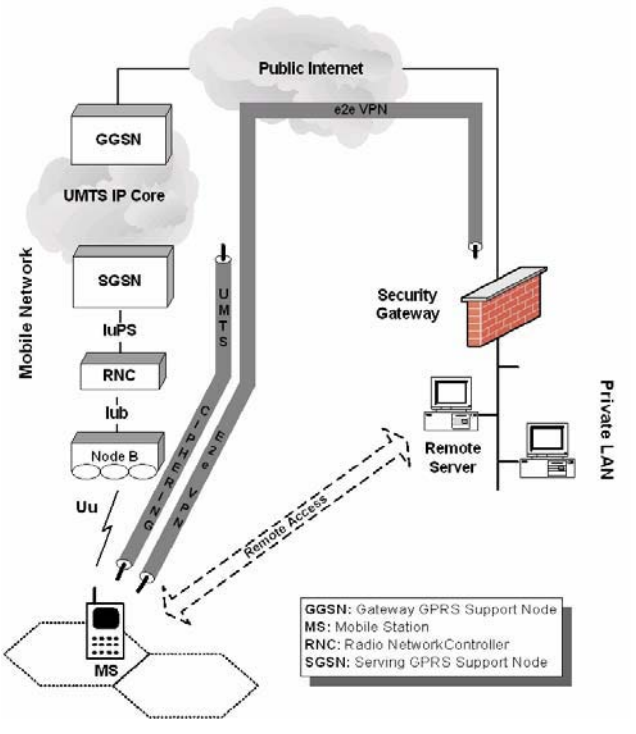


An alternative approach to the previous solutions that employ security at the application layer pertains to these that employ security at the network layer. The most prominent technique for providing security at the network layer is IPsec (Kent & Atkinson, 1998). As a network layer security mechanism, IPsec protects traffic on a per connection basis and thus, is independent from the applications that run above it. In addition, IPsec is used for implementation of VPNs (Gleeson et al., 2000). An IPsec-based VPN is used for the authentication and the authorization of user access to corporate resources, the establishment of secure tunnels between the communicating parties and the encapsulation and protection of the data transmitted by the network. On-demand VPNs that are tailored to specific security needs are especially useful for UMTS users, which require any-to-any connectivity in an ad hoc fashion. Regarding the deployment of VPNs over the UMTS infrastructure, three alternative security schemes have been proposed: (1) the end-to-end (Xenakis & Merakos, 2004a), (2) the network-wide (Xenakis & Merakos, 2006), and (3) the border-based (Xenakis, Loukas, & Merakos 2006). These schemes mainly differ in the position where the security functionality is placed within the UMTS network architecture (MS, RNC, and GGSN), and whether data in transit are ever in cleartext or available to be tapped by outsiders.

The end-to-end security scheme integrates the VPN functionality into the communicating peers, which negotiate and apply security. More specifically, an MS and a remote security gateway (SG) of a corporate private network establish a pair of IPsec SAs between them, which are extended over the entire multi-nature communication path, as shown in Figure 12. Thus, sensitive data are secured as they leave the originator site (MS or SG) and remain protected while they are conveyed over the radio interface, the GPRS backbone network, and the public Internet eliminating the possibilities of being intercepted or to be altered by anyone.

The deployed end-to-end VPN has no interrelation with the underlying network operation

Figure 12. The end-to-end security scheme



and the provided network connectivity. It operates above the network layer and thus, the security parameters, which are contained within the IPsec SA, are not affected by the MS movement. For this reason the MS may freely move within the UMTS coverage area maintaining network connectivity and VPN service provision. The UMTS mobility management procedures keep track of the user location and therefore, the incoming packets are routed to the MS. On the other hand, the end-to-end security scheme is not compatible with the legal interception option or any other application that requires access to the traversing data within the mobile network. The enforcement of network security policy, traditionally performed by border firewalls, is devolved to end hosts, which establish VPN overlays. Despite this, the border firewalls remain to perform packet filtering and counteract against denial of service attacks.

Contrary to the end-to-end security scheme, the network-wide (Xenakis & Merakos, 2006) and the border-based (Xenakis et al., 2006) schemes integrate the VPN functionality into the UMTS network infrastructure following a network-assisted security model. In both schemes a MS initiates a VPN that is negotiated and established by the network infrastructure thus minimizing the impact to end users and their devices. The network operators provide the security aggregation facilities, which are shared among the network subscribers, as a complementary service, granting-added value. They have solid network management expertise and more resources to effectively create, deploy, and manage VPN services originating from mobile subscribers.

For the deployment of both security schemes (i.e., network-wide and border-based) the MS must be enhanced with a security client (SecC) and the UMTS core network should incorporate a security server (SecS). The SecC is employed by the user to request for VPN services and express his preferences. It is a lightweight module that does not

Figure 13. The network-wide security scheme

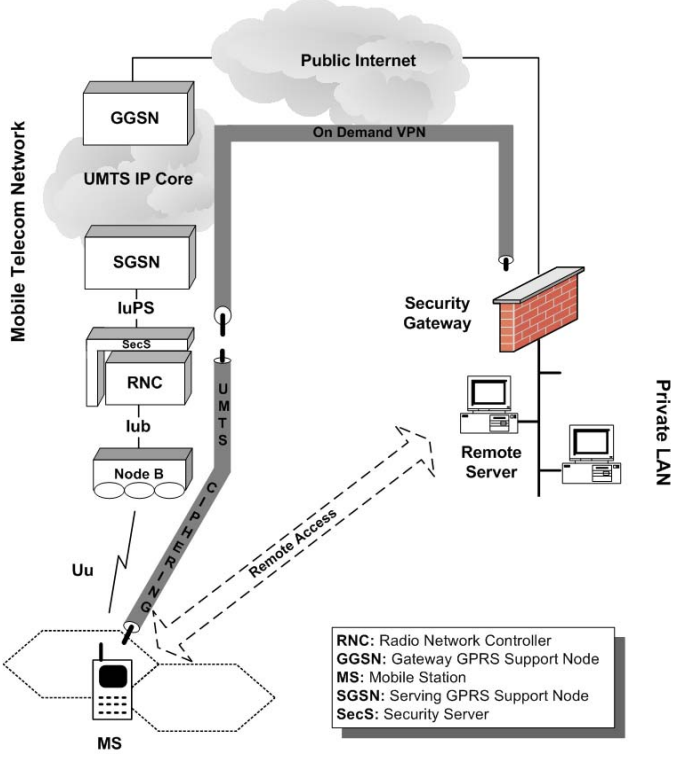
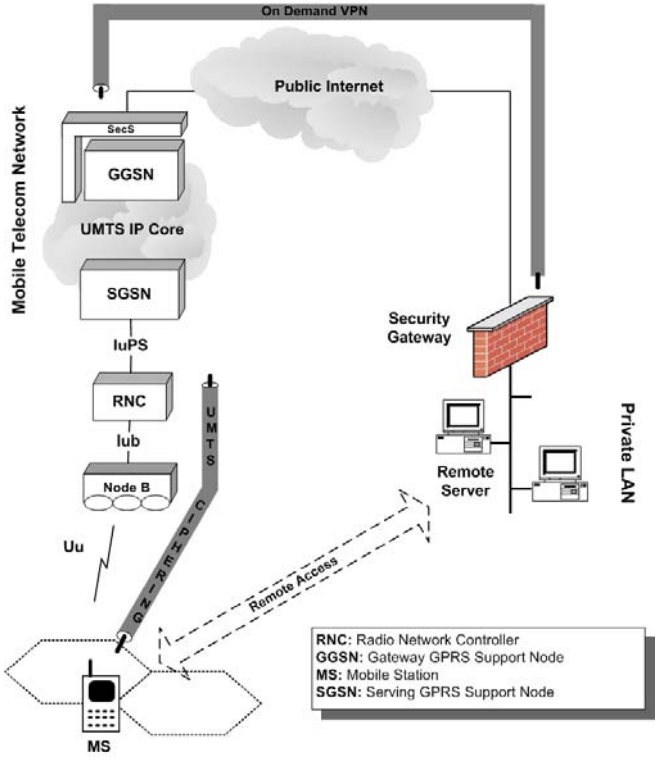


Figure 14. The border-based security scheme



entail considerable processing and memory capabilities and thus, it can be easily integrated in any type of mobile device causing minor performance overhead. On the other side, the SecS establishes, controls, and manages VPNs between itself and remote SGs at corporate LANs on behalf of the mobile users. The SecS comprises an IPsec implementation modified to adapt to the client-initiated VPN scheme and the security service provision in a mobile UMTS environment. It can be readily integrated in the existing network infrastructure and thus, both schemes can be employed as add-on features of UMTS.

The network-wide scheme (see Figure 13) integrates the SecS into the RNC of the UMTS network infrastructure. This scheme provides maximal security services to the communicating peers by employing the existing UMTS ciphering over the radio interface and extending a VPN over the UMTS backbone and the public Internet. Thus, sensitive user data remains encrypted for the entire network route between the originator and the recipient. In order to achieve VPN continuity as a mobile user moves and roams, the standard UMTS mobility management procedures needs to be enhanced. The enhancements include the transfer of the related context (named as security context), which contains the details of the deployed security associations that pertain to the moving user, to the new visited access point. This transfer enables the reconstruction of the security associations of the moving user to the new visited access point, when the user connects to it, providing continuous VPN services from the end-user perspective. The network-wide scheme is compatible with legal interception; however, User Datagram Protocol (UDP) encapsulation is applied for Network Address Translation (NAT) traversal. Finally, the network security policy is enforced by the SGSN, which incorporates the SecS.

By placing the SecS in the GGSN, the border-based VPN deployment scheme is realized (see

Figure 14). This scheme protects data conveyance over the public Internet, which is a vulnerable network segment. The user mobility is transparent to the VPN operation, as long as the user remains under the same network operator coverage and is served by the same GGSN. However, whenever the mobile user roams to another GGSN, the existing security association cannot be used and a new VPN should be established. The border-based scheme is compatible with the legal interception option and NAT presence. Moreover, since the SecS resides at the GGSN, it also provides firewall services to the UMTS network applying network security policy.

CONCLUSION

The evolution of 3G networks signifies a shift towards open and easily accessible network architectures, which raise major security concerns. To address these concerns, a specific security architecture named as 3G security architecture has been designed. This chapter has presented an analysis of the 3G security architecture. This architecture comprises a set of mechanisms that attempt to ensure that all information generated by or relating to a user, as well as the resources and services provided by the serving network and the home environment, are adequately protected against misuse or misappropriation. In addition to these mechanisms, a set of traditional security technologies designed for fixed and wireless networks can also be applied to protect 3G networks. Based on the carried analysis, the critical points in the 3G-security architecture, which might cause network and service vulnerability, have been outlined. Finally, the current research activities on the UMTS security that aim at improving the UMTS security architecture have been briefly presented.

ACKNOWLEDGMENT

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KEY TERMS

International mobile subscriber identity (IMSI): IMSI is a unique number associated with all UMTS network mobile phone users.

Internet key exchange (IKE): IKE is a protocol used to set up a security association (SA) in the IPsec protocol suite.

IP security (IPsec): IPsec is a suite of protocols for securing IP communications by authenticating and/or encrypting each IP packet in a data stream.

Temporary mobile subscriber identity (TMSI): TMSI is a randomly allocated number that is given to the mobile the moment it is switched on and serves as a temporary identity between the mobile and the network.

Third generation (3G): 3G is a technology in the context of mobile phone standards. The services associated with 3G include wide-area wireless voice telephony and broadband wireless data, all in a mobile environment.

Universal mobile telecommunications system (UMTS): UMTS is one of the 3G mobile phone technologies.

Universal subscriber identity module (USIM): USIM is an application for UMTS mobile telephony running on a UICC smart card which is inserted in a 3G mobile phone and stores user subscriber information and authentication information.

Wideband code division multiple access (WCDMA): WCDMA is a wideband spread-spectrum mobile air interface that utilizes the direct sequence code division multiple access (CDMA) signaling method to achieve higher speeds and support more users compared to the implementation of time division multiplexing (TDMA) used by 2G GSM networks.

ENDNOTES

1 $\|$ String concatenation.

2 $\oplus$ Exclusive or

Chapter XXI
Access Security in UMTS and IMS

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INTRODUCTION

Motivated by the requirements for higher data rate, richer multimedia services, and broader radio range wireless mobile networks are currently in the stage evolving from the second-generation (2G), for example, global system for mobile communications (GSM), into the era of third-generation (3G) or beyond 3G or fourth-generation (4G). Universal mobile telecommunications system (UMTS) is the natural successor of the current popular GSM (http://www.3gpp.org) code division multiple access 2000 (CDMA2000) is the next generation version for the CDMA-95, which is predominantly deployed in North America and North Korea. Time division-sychrononous CDMA (TD-SCDMA) is in the framework of 3rd generation partnership project 2 (3GPP2) and is expected to be one of the principle wireless technologies employed in China in the future (http://www.3gpp.org; 3G TS 35.206). It is envisioned that each of three standards in the framework of international mobile telecommunications-2000 (IMT-2000) will play a significant role in the future due to the backward compatibility, investment, maintenance cost, and even politics. In all of the potential standards, access security is one of the primary demands as well as challenges

to resolve the deficiency existing in the second generation wireless mobile networks such as GSM, in which only one-way authentication is performed for the core network part to verify the user equipment (UE) (3G TS 24.008). Such access security may lead to the "man-in-middle" problem, which is a type of attack that can take place when two clients are communicating remotely and exchange public keys in order to initialize secure communications. If both of the two public keys are intercepted in the route by someone, he/she can act as a conduit and send in the messages with his/her own faked public key. As a result, the secure communication is eavesdropped by a third party.

Multimedia service provisioning is one of the primary demands and motivations for the next generation wireless networks. To achieve this goal, the IP multimedia subsystem (IMS) is added as the core network in UMTS providing the multimedia service, for example, voice telephony, video conference, real-time streaming media, interactive game, voice over IP, picture, HTTP, and instant messaging (3G TS 33.203). The multimedia session management, initialization, and termination are specified and implemented in the session initiation protocol (SIP) (3G TS 29.228; Zhang & Fang, 2005). To ensure the secure communication in a multimedia session, an efficient access security mechanism shall be also provided.

In this chapter, we make an introduction to the access security in the next generation wireless mobile networks, including the mechanisms in the circuited-switched domain, packet-switched domain, and also the emerging IMS domain.

BACKGROUND OVERVIEW

Figure 1 shows the UMTS network architecture with most related components in security management (3G TS 29.002; 3G TS 33.102). User terminal (UE) utilizes the circuited-switched or packet-switched service through the radio interface between base station (BS) and itself. BS locates in the center of a cell which coveres a radio range. BS provides the wireless access point for UEs to the core network. Radio network controller (RNC) monitors and supervises the activities of several BS under its management. Radio access network (RAN) consists of the RNC and the associated BS under the RNC. Home location register (HLR) stores the permanent information for the subscrib-

Figure 1. UMTS network architecture

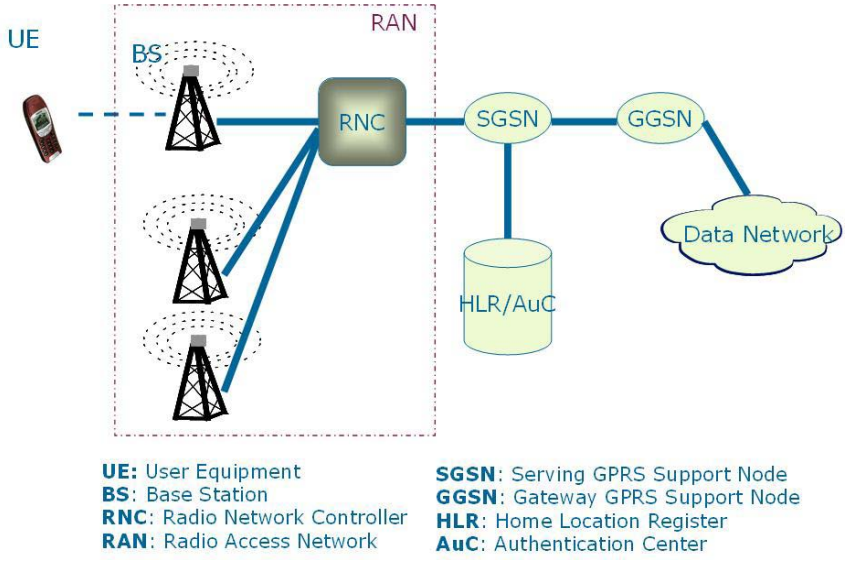


Figure 2. UMTS network authentication and key agreement (AKA)

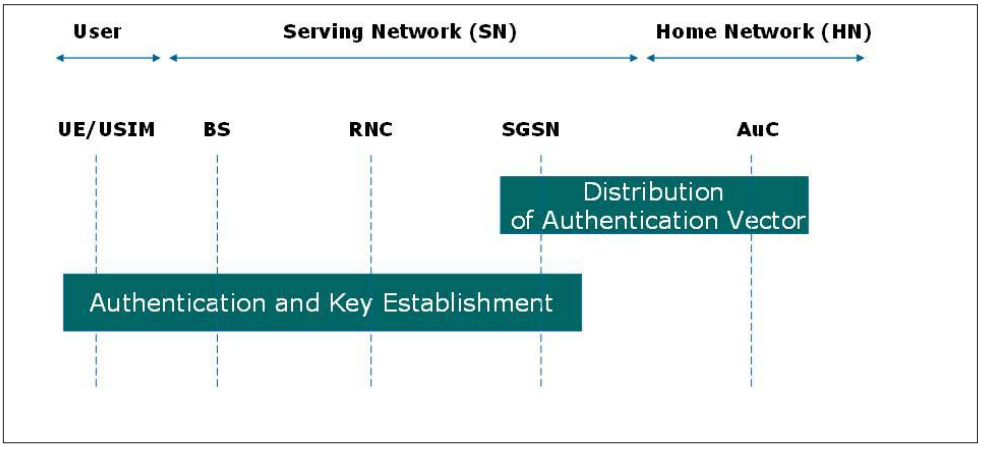
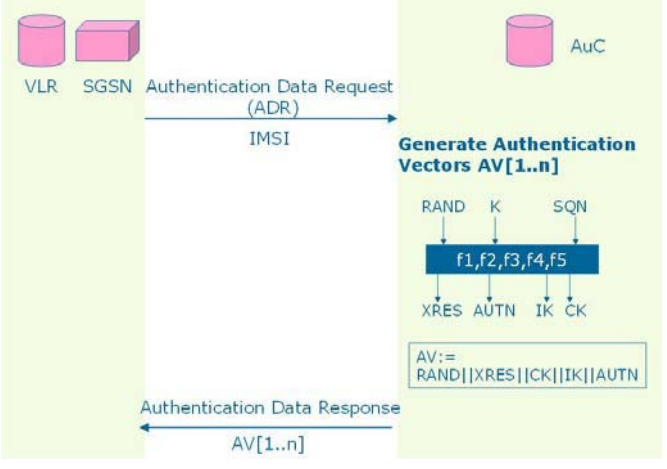


Figure 3. AKA phase 1: Distribution of authentication vector

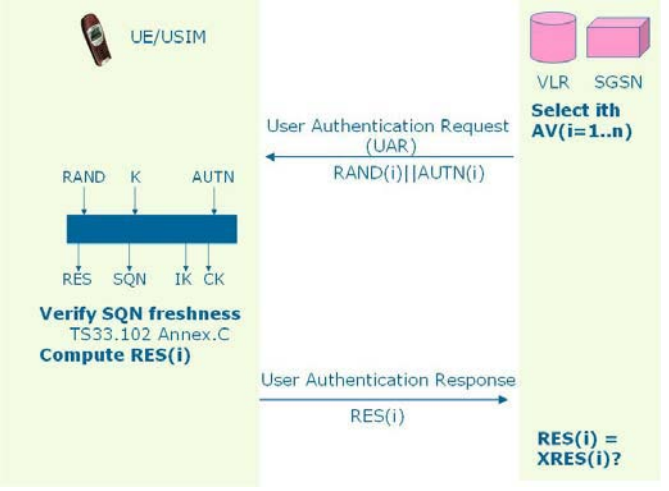


ers, for example, International Mobile Subscriber Identity (IMSI), subscribed service profile, and identity of current location area. Authentication center (AuC) is responsible to verify the validness of user's activity including call behavior and location management. Normally, HLR and AuC locates in the same database/server. Serving GPRS support node (SGSN) connects the core network and the radio access network and is responsible for location management and for delivering packets between UE and the core network. Gateway GPRS support node (GGSN) acts similar as a gateway between core network and the external IP networks such as Internet, telecommunication networks, and enterprise intranets.

ACCESS SECURITY IN UMTS

Figure 2 shows the most signicant feature in the framework of UMTS security management, that is, authentication and key agreement (AKA) (3G TS 24.008). Authentication refers to the mutual authentication mechanism that the subscriber is able to use to authenticate the network, and the network is also able to authenticate the user. Key agreement refers to the mechanism to generate the cipher key and integrity key. The events for triggering the AKA process include location update request, user registration, service request, attach request, detach request, and connection re-establishment request.

Figure 4. AKA phase 2: Authentication and key establishment



The authentication protocol is based on a permanent secret key **K** (128-bit) that is shared between the UE and HLR/AuC. The AKA mechanism can be divided into two phases: the distribution of authentication vector (DAV) from the HLR/AuC to the SGSN as shown in Figure 3, and the authentication and key establishment between the UE and the core network as illustrated in Figure 4.

Distribution of Authentication Vector

When a UE leaves an old SGSN (SGSNo) and moves into the coverage of a new SGSN (SGSNn), SGSNn has no corresponding record for the UE, which makes it necessary to authenticate the UE prior to the subsequent behavior. SGSNn will delivery the message authentication data request (ADR) to the HLR/AuC with the UE's unique IMSI. Based on the received IMSI, AuC can find the associated record in its database and hence the according master key **K** for this particular UE. Then, HLR/AuC generates the number of **n** AV instead of single one AV for the sake of saving signaling overhead. The AV structure is comprised of five components: (1) a random number **RAND**, (2) an expected authentication response **XRES**, (3) a cipher key **CK**, (4) an integrity key **IK,** and (5) a network authentication token **AUTN** (3G TS 23.060). In each generation, an AV is calculated by means of the authentication function f1-f5, where for instance the function f1 is employed to compute XRES, the function f2 is used to compute **RES**, and the function f3 is used to compute **CK** (3G TS 33.105; 3G TS 35.205; 3G TS 35.206). After successfully generating **n** AVs, AuC sends back the AV array to SGSNn via the message authentication data response, and SGSNn saves these **n** AVs for the particular UE. It is noteworthy that this phase executes not only upon UE entering a new SGSN area, but also when there are no AVs available upon an action arrival which requires authentication.

Authentication and Key Establishment

For each activity triggering authentication request such as call origination, paging, or location update the SGSN initiates the challenge user authentication request (UAR) message to the UE with the parameters **RAND** and **AUTN**, which is retrieved from the i^{th} (i = 1,2,…n) AV in the first-in-first-out (FIFO) manner. Upon receiving the AV, the UE checks the validity of **AUTN**. For this goal, the UE retrieves SQN component from **AUTN** and calculates expected message authentication code for authentication (XMAC-A). The UE then compares X-MAC-A and message authentication

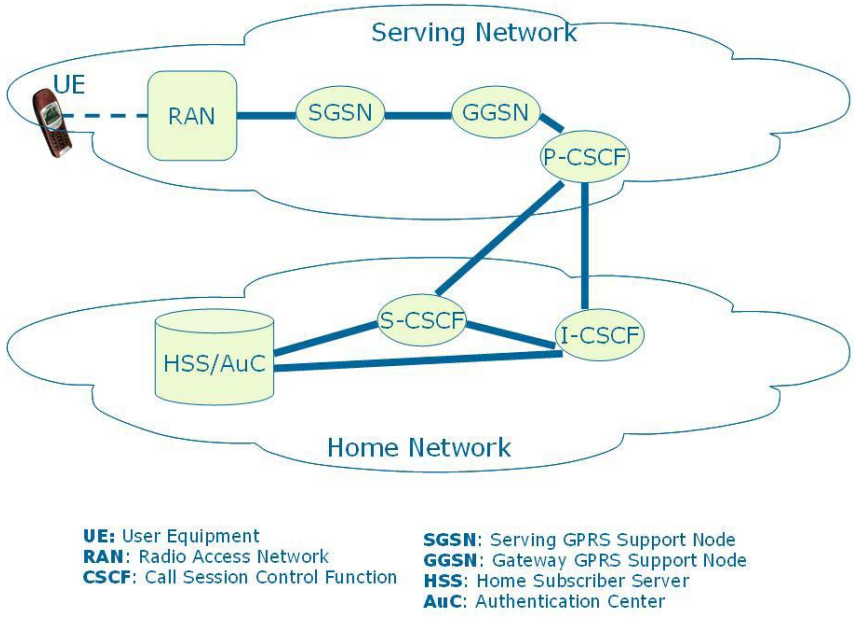
code for authentication (MAC-A) component in **AUTN**, if they are equal to each other, then the network is verified. Otherwise, the UE rejects the UAR and hence the network. After the network is identified, UE checks the SQN freshness, that is, the SQN has never been used before. When the network succeeds, the UE then computes the authentication response **RES** from the received **RAND** value and sends it in a *user authentication response* message to the SGSN. If **RES** equals the expected response **XRES**, then the UE is successfully authenticated. Since there are **n** AVs generated and recorded in SGSNn during each operation of DAV while only one AV is used during an authentication event, the signaling between SGSN and **HLR/AuC** during DAV is not needed for every authentication event.

It is believed that, after the AKA procedure, all messages are claimed integrity protection, and the signaling data as well as user data are confidentiality protection. In the sense of integrity protection, the content of signaling messages should not be manipulated. With regard to confidentiality protection, the subscriber identification, location, user data, and signaling data should be encrypted.

ACCESS SECURITY IN IMS

There are three entities relevant to the IMS security architecture (see Figure 5). A proxy call session control function (P-CSCF) locates in the serving network of a UE and acts as the first access point in the serving network. P-CSCF is responsible for forwarding SIP messages of an UE to the home network. A serving call session control function (S-CSCF) locates in the home network to provide session control of multimedia services and acts as SIP registrar or SIP proxy server. The S-CSCF sends messages toward the home subscriber server (HSS) and the AuC to receive subscriber data and authentication information. An interrogating call session control function (I-CSCF) locates in the home network and acts as a SIP proxy toward the home network. I-CSCF is responsible for selecting an appropriate S-CSCF for the UE and forwarding SIP requests/responses toward the S-CSCF.

Figure 5. IMS network architecture



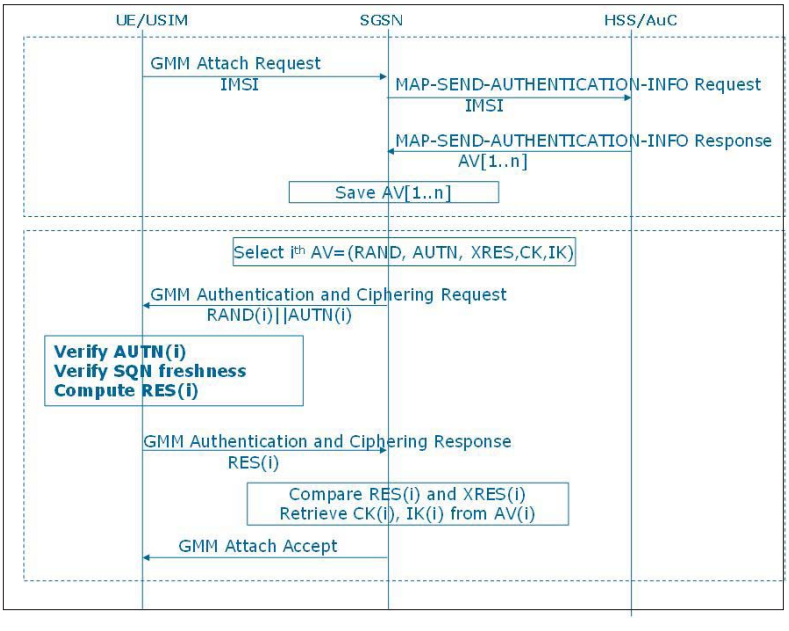
Different from the one-pass authentication procedure in AKA illustrated in Figure 2, the security in IMS is a two-pass authentication procedure, including general packet radio servcie (GPRS) authentication and IMS authentication (3G TS 29.229). Before utilizing the IMS service, a UE should first setup a data connection to know the IP address of P-CSCF and to carry the SIP signaling messages through the P-CSCF. The data connection establishment is comprised of two steps, that is, attach and packet data protocol (PDP) context activation. The first phase attach is used to establish mobility management context between the UE and SGSN. During this procedure, the UE should perform GPRS authentication and GPRS registration to verify its validness and retrieve the subscriber profile including subscribed services, quality of service (QoS) profile, IP address, and so on. Once the UE is attached, the second step PDP context activation is followed to activate a PDP address and build the association between the SGSN and GGSN. Only after attached and PDP context activation, an UE can access IMS services through registration process. The registration is necessary to inform the HSS the location, authenticate and download subscriber profile to S-CSCF. We will discuss the GPRS authentication and IMS authentication in the following two subsections. The discussion of either GPRS registration or PDP context activation is out of the scope and the readers are suggested to refer to the related technical specifications (3G TS 33.102).

GPRS AUTHENTICATION

GPRS authentication is performed in the framework of GPRS mobility management (GMM) (http://www.3gpp2.org; 3G TS 33.102). Figure 6 shows the messages sequence in GPRS authentication. In particular, the steps include:

1. The UE sends **GMM Attach Request (IMSI)** to the SGSN with the unique identity **IMSI**.
2. If the SGSN has at least one AV for the UE, then step 2 and 3 are skipped. Otherwise, the SGSN has to obtain AVs from the entity HSS/AuC. SGSN triggers the procedure DAV by sending a **MAP-SEND-AUTHENTICA-**

Figure 6. GPRS authentication



TION-INFO Request (IMSI) message to the HLR/AuC with the parameter **IMSI** uniquely identifying the UE.

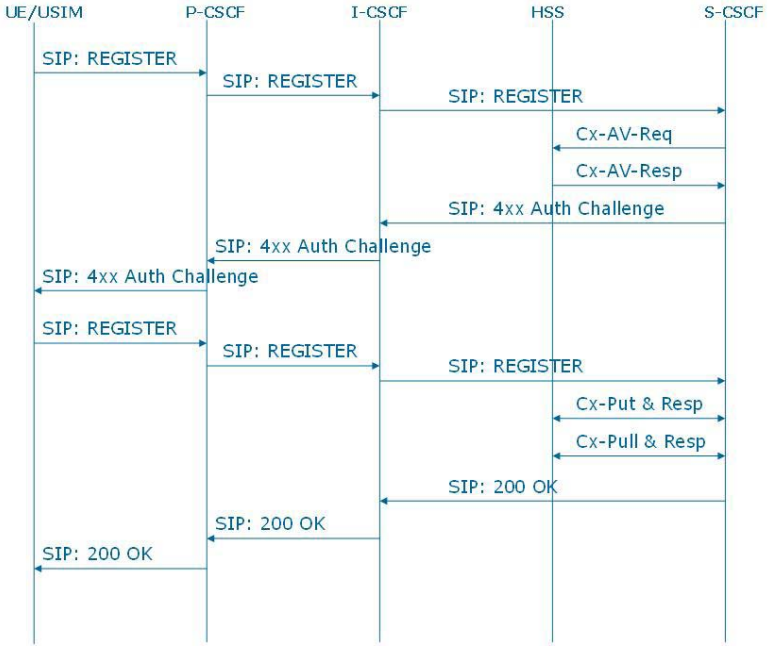
3. Upon receiving the authentication request, the HSS/AuC searches the according record in the database on the basis of **IMSI**. Then, HSS/AuC generates an ordered array of **n** AVs for the specific UE. Each AV consists of the following components: a random number **RAND**, an expected response **XRES**, a cipher key **CK**, an integrity key **IK,** and an authentication token **AUTN**. The HSS/AuC then sends back the message **MAP-SEND-AUTHENTICATION-INFO Response** to SGSN with the AV array as parameters.
4. SGSN stores these **n** AVs for the particular UE and shall choose the next unused AV in the ordered AV array. Subsequently, the SGSN shall challenge the UE and sends message **GMM Authentication and Ciphering Request** with parameters **RAND** and **AUTN** populated from the selected AV.
5. The UE checks the validness of the received **AUTN**. In case it is acceptable, the UE shall calculate a response **RES** and send back to the SGSN through the message **GMM Authentication and Ciphering Response**. The SGSN retrieves the expected response **XRES** from the selected AV and compares **XRES** with the received response **RES**. If they match, the authentication and key agreement is successfully completed and the keys **CK** and **IK** are retrieved for the following signaling confidentiality and integrity protection.
6. The SGSN sends a **GMM Attach Accept** message to the UE to indicate the completion of the successful attach procedure.

IMS AUTHENTICATION

After the procedures of GPRS authentication, GPRS registration and PDP context activation, the UE has the IP address of the P-CSCF and is able to access the IMS services through the registration procedure using SIP and Cx commands as shown in Figure 7 (CWTS TSM 03.20; 3G TS 29.229). This procedure includes the IMS authentication and the IMS registration. In particular, the steps include:

1. To start registration, the UE sends a **SIP REGISTER (IMPI, IMPU)** message to the P-CSCF in the serving network. On the receipt, the P-CSCF forwards the registration request to the I-CSCF of the home network. I-CSCF then delivers the message to a chosen S-CSCF.
2. If the S-CSCF has at least one AV for the UE, then steps 2 and 3 are skipped. Otherwise, the S-CSCF has to obtain AVs from the entity HSS/AuC. S-CSCF triggers the procedure DAV by sending a **Cx-AV-Req(IMPI, n)** message to the HSS/AuC with the parameter **IMPI** uniquely identifying the UE and the number of **n** AVs wanted.
3. Upon receipt of a request from the S-CSCF, the HSS/AuC searches the database on the basis of the unique **IMPI**, obtains the subscriber profile, and generates an ordered array of **n** AVs for the specific UE. Each AV consists of the following components: a random number **RAND**, an expected response **XRES**, a cipher key **CK**, an integrity key **IK,** and an authentication token **AUTN**. Each AV is good for only one authentication and key agreement between the IMS subscriber and the S-CSCF. The HSS/AuC then sends back the message **Cx-AV-Req-Resp(IMPI, RAND1||AUTN1||XRES1||CK1||IK1,…, RANDn||AUTNn||XRESn||CKn||IKn)** to the S-CSCF with the array of AV as parameters.
4. The S-CSCF chooses the first unused AV in the array of AVs based on FIFO policy. From the selected AV, the items **RAND, AUTN, IK,** and **CK** are populated. The S-CSCF sends the message **SIP 4xx-Auth-Challenge (IMPI, RAND, AUTN, IK, CK)** to the I-CSCF, which then forwards the message to P-CSCF. Upon the receipt, the P-CSCF shall store the two keys **IK** and **CK** and remove the key information and finally forward the

Figure 7. IMS authentication



rest of the message **SIP 4xx-Auth-Challenge (IMPI, RAND, AUTN)** to the UE.

5. The UE verifies the freshness of the received **AUTN** and calculates a response **RES**. This result **RES** is sent back from the UE to the P-CSCF through the message **SIP REGISTER (IMPI, RES)**. After receiving the request, the P-CSCF forwards it to the I-CSCF, which further forwards the authentication response to the S-CSCF. The S-CSCF retrieves the expected response **XRES** and compares **XRES** and the received response **RES**. If they match, the authentication and key agreement is successfully completed. Next three steps perform registration.
6. The S-CSCF sends a **Cx-Put** message to the HSS/AuC with the UE identity. The HSS shall store the S-CSCF name, which is presently serving the UE, and then sends the **Cx-Put Response** for acknowledgement.
7. Next, the S-CSCF sends a **Cx-Pull** to the HSS/AuC with the UE identity in order to download the related information in the subscriber profile to the S-CSCF. HSS shall send a **Cx-Pull Response** to the S-CSCF with the indicated information.
8. The S-CSCF sends **SIP 200 OK** message to the UE through the I-CSCF and P-CSCF. After this step, a security associate (SA) is active for the protection of subsequent SIP messages between the UE and the P-CSCF.

FUTURE TRENDS

Security Management in Heterogeneous Network

The next generation wireless mobile networks are characterized as the co-existent of the variety of network architectures, protocols, and applications due to the diverse requirements for data rate, radio coverage, deployment cost, and multimedia service. The 3GPP is actively specifying the roaming mechanism in the integrated wireless LAN (WLAN)/UMTS networks. It should be noted

that this scenario is only a specific heterogeneous network. The IEEE 802.16 standard is an emerging broadband wireless access system specified for wireless metropolitan area networks (WMAN) with the aim to bridge the last mile, replacing costly wireline and also providing high speed multimedia services in fast moving transportation. The recently amended 802.16e adds a mobility component for WMAN and defines both physical and MAC layers for combined fixed and mobile operations in licensed bands. It is envisaged that the future generation wireless networks is the flexible and seamless integration of the three technologies WLAN, WMAN, and wireless wide area network (WWAN), where WLAN (e.g., IEEE 802.11 Wi-Fi) serves as the hot-spot access area for short-range and very high speed; WMAN (e.g., IEEE 802.16 WiMAX) serves as the metropolitan-wide access network with high data rate and WWAN (e.g., UMTS) provides the national-wide network with relatively low data rate. The substantial technical challenge is to design and implement the security architectures and protocols across such heterogeneous networks taking into account the seamless mobility, scalability, and performance efficiency.

Security-Mobility Management Interaction and Security-Energy Tradeoff

The performance of security management has a close interaction with the framework of mobility management. Mobility management includes two components: location management and handoff management (http:www.3gpp2.org). There are two operations in the location management: updating the UE location and paging the UE. In UMTS, SGSN shall authenticate a UE when the SGSN receives an "Initial L3 message" sent from UE. This message is triggered by the actions, including location update request, connection management request, routing area update request, attach request, and paging response. It is clear that all these events are closely relevant to the user's mobility management architecture and mechanism. Liang and Wang (2005) constructed an analytical model to evaluate the impact of authentication on the security and QoS. The authors introduced the system model based on the widely used challenge/response mechanism. Then, a concept of security level is introduced to describe the different level of communication protection with regard to the nature of security, that is, information secrecy, data integrity, and resource availability. By taking traffic and mobility patterns into account, the technique establishes a quantitative connection between the security and QoS through the authentication and facilitates the evaluation of overall system performance under diverse security levels, mobility and traffic processes.

Generally, a UE is powered by battery and hence the mechanism in efficiently utilizing the limited energy is becoming very important. In case of more frequent authentication to increase the security, the UE will consume more energy. With fewer authentications incurring potential vulnerability, the UE is able to enlarge its lifetime before re-charging. As a consequence, there is a trade-off between the security and energy management. Potlapally, Ravi, Raghunathan, and Jha (2003) provided energy consumption empirical measurements for a variety of ciphers, hash functions, and signature algorithms. Based on the observations, the study presented some reasoning about the energy-security trade-offs in determining key length. However, no analytical models have been proposed to evaluate the energy-security trade-offs or make the intelligent decision on trade-off.

Higher Security Protocols

Although AKA has been standardized, the protocol has two significant weaknesses: (1) HLR/AuC does not verify whether the information sent from the visiting location register (VLR)/SGSN is valid or not. That is, AKA has assumed that the link between VLR/SGSN and HLR/AuC is adequately reliable; and (2) for the UMTS integrity protection mechanism, integrity key is transmitted without encryption and the user data are not protected. New strategies shall be designed to address these issues.

Harn and Hsin (2003) identified and discussed the inefficiency and complexity in keeping and managing the sequence number during the network authentication. Based on the combination of hash chaining and keyed-hash message authentication code techniques, an enhanced scheme is proposed to simplify the protocol implementation and simultaneously provide strong periodically mutual authentication.

Zhang and Fang (2005) showed that the 3GPP AKA protocol is vulnerable to a variant of the fake BS attack. The vulnerability allows an adversary to redirect user traffic from one network to another and to re-use corrupted AVs from one network to all other networks. To address such security problems in the current 3GPP AKA, the authors presented a new authentication and key agreement protocol AP-AKA which defeats redirection attack and drastically lowers the impact of network corruption.

Security Protocols Performance

Security architecture and protocol are normally evaluated to guarantee the security, confidentiality, and integrity requirement. Recently, a few studies have appeared to investigate the authentication signaling traffic performance due to the rapidly increasing number of subscribers and consequently potentially high authentication requests and heavy burden on the signaling networks. Lin and Chen (2003) argue the disadvantages in fetching the constant number of AV from HLR/AuC. Based on the observations of the mobility pattern, the authors proposed an adaptive scheme to generate an optimal number of AV array, which is able to significantly reduce the authentication signaling traffic and hence save the limited bandwidth utilization. Zhang and Fujise (2006) argue the long delay problem and proposed a mechanism to address the issue. In particular, when the two entities SGSN and HLR/AuC locate far away from each other, the response for an available AV may be potentially very long. The consequence of long delay includes call blocking and location update failure, and hence degraded QoS. To address this problem, the study proposed an enhanced scheme to fetch AV earlier before all AVs are used up. Comparing with the original 3GPP Technical Specification TS33.102 (2000), the proposed strategy is able to achieve very low probability in waiting for an available AV with negligible increased signaling overhead and low storage cost. The study in Al-Saraireh and Yousef (2006) also analyzes the transmission overhead during the procedure of AKA. It is proposed that security protocols performance should be evaluated from the security perspective and also from the signaling overhead point of view. New security protocols should consider to combat potential vulnerability as well as to introduce low additional signaling cost.

CONCLUSION

This chapter gives an overview on the security management in the next generation wireless networks. The AKA process is described and its extension in GPRS authentication and IMS authentication are further discussed in detail. The identified research challenges shall serve as the guidance for the further study to propose more efficient security protocols taking into account the network architecture heterogeneity, the energy-security trade-offs, the mobility-security interaction, and comprehensive performance evaluation.

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KEY TERMS

Access security: Access security is the mechanism that provides mobile users with secure access to wireless services and protects against attacks on the radio access interface.

General Packet Radio Service (GPRS): GPRS is regarded as 2.5 generation mobile system. It provides mobile data service to GSM users.

IP multimedia subsystem (IMS): IMS is the component to support multimedia services in 3G system.

Third generation (3G): 3G wireless communication systems is standardized to support multimedia services with high data rate.

Universal mobile telecommunications system (UMTS): UMTS is one of the third-generation wireless communication systems.

Chapter XXII
Security in 2.5G Mobile Systems

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ABSTRACT

The global system for mobile communications (GSM) is the most popular standard that implements second generation (2G) cellular systems. 2G systems combined with general packet radio services (GPRS) are often described as 2.5G, that is, a technology between the 2G and third generation (3G) of mobile systems. GPRS is a service that provides packet radio access for GSM users. This chapter presents the security architecture employed in 2.5G mobile systems focusing on GPRS. More specifically, the security measures applied to protect the mobile users, the radio access network, the fixed part of the network, and the related data of GPRS are presented and analyzed in detail. This analysis reveals the security weaknesses of the applied measures that may lead to the realization of security attacks by adversaries. These attacks threaten network operation and data transfer through it, compromising end users and network security. To defeat the identified risks, current research activities on the GPRS security propose a set of security improvements to the existing GPRS security architecture.

INTRODUCTION

The global system for mobile communications, (GSM) is the most popular standard that implements second generation (2G) cellular systems. 2G systems combined with general packet radio services (GPRS) (3GPP TS 03.6, 2002) are often described as 2.5G, that is, a technology between the 2G and third generation (3G) of mobile systems. GPRS is a service that provides packet radio access for GSM users. The GPRS network architecture, which constitutes a migration step toward 3G systems, consists of an overlay network onto the GSM network. In the wireless part, the GPRS technology reserves radio resources only when there is data to be sent, thus, ensuring the optimized utilization of radio resources. The fixed part of the network employs the IP technology and is connected to the public Internet. Taking advantage of these features, GPRS enables the provision of a variety of packet-oriented multimedia applications and services to mobile users, realizing the concept of the mobile Internet.

For the successful implementation of the new emerging applications and services over GPRS, security is considered as a vital factor. This is because of the fact that wireless access is inherently less secure and the radio transmission is by nature more susceptible to eavesdropping and fraud in use than wire-line transmission. In addition, users' mobility and the universal access to the network imply higher security risks compared to those encountered in fixed networks. In order to meet security objectives, GPRS uses a specific security architecture, which aims at protecting the network against unauthorized access and the privacy of users. This architecture is mainly based on the security measures applied in GSM, since the GPRS system is built on the GSM infrastructure.

Based on the aforementioned consideration, the majority of the existing literature on security in 2.5G systems refers to GSM (Mitchell, 2001; Pagliusi, 2002). However, GPRS differs from GSM in certain operational and service points, which require a different security analysis. This is because GPRS is based on IP, which is an open and wide deployed technology that presents many vulnerable points. Similarly to IP networks, intruders to the GPRS system may attempt to breach the confidentiality, integrity, or availability, or otherwise attempt to abuse the system in order to compromise services, defraud users, or any part of it. Thus, the GPRS system is more exposed to intruders compared to GSM.

This chapter presents the security architecture employed in 2.5G mobile systems focusing on GPRS. More specifically, the security measures applied to protect the mobile users, the radio access network, the fixed part of the network, and the related data of GPRS are presented and analyzed in details. This analysis reveals the security weaknesses of the applied measures that may lead to the realization of security attacks by adversaries. These attacks threaten network operation and data transfer through it, compromising end users and network security. To defeat the identified risks, current research activities on the GPRS security propose a set of security improvements to the existing GPRS security architecture. The rest of this chapter is organized as follows. The next section describes briefly the GPRS network architecture. The third section presents the security architecture applied to GPRS and the fourth section analyzes its security weaknesses. The fifth section elaborates on the current research activities on the GPRS security and the sixth section presents the conclusions.

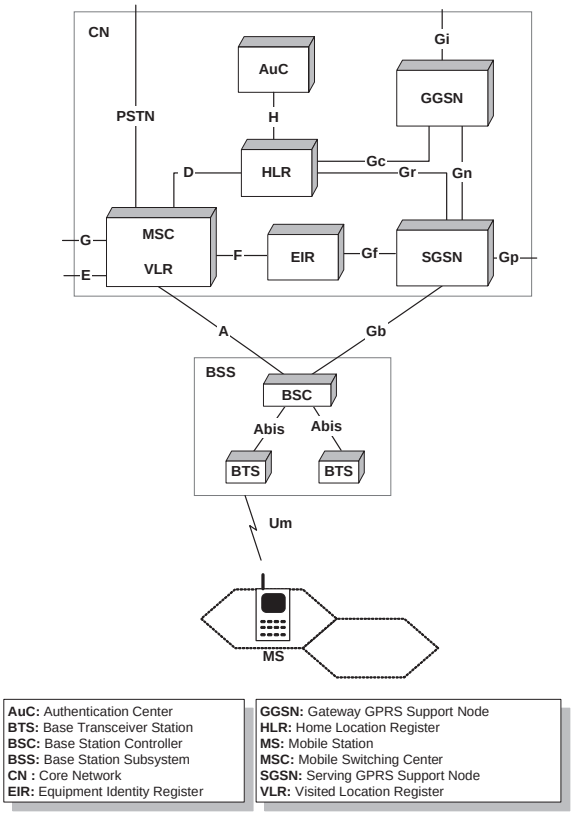
GPRS NETWORK ARCHITECTURE

The network architecture of GPRS (3GPP TS 03.6, 2002) is presented in Figure 1. A GPRS user owns a mobile station (MS) that provides access to the wireless network. From the network side, the base station subsystem (BSS) is a network part that is responsible for the control of the radio path. BSS consists of two types of nodes: the base station controller (BSC) and the base transceiver station (BTS). BTS is responsible for the radio coverage of a given geographical area, while BSC maintains radio connections towards MSs and terrestrial connections towards the fixed part of the network (core network).

The GPRS core network (CN) uses the network elements of GSM such as the home location register (HLR), the visitor location register (VLR), the authentication centre (AuC) and the equipment identity register (EIR). HLR is a database used for the management of permanent data of mobile users. VLR is a database of the service area visited by an MS and contains all the related information required for the MS service handling. AuC maintains security information related to subscribers identity, while EIR maintains information related to mobile equipments' identity. Finally, the mobile service switching centre (MSC) is a network element responsible for circuit-switched services (e.g., voice call) (3GPP TS 03.6, 2002).

As presented previously, GPRS reuses the majority of the GSM network infrastructure. However, in order to build a packet-oriented mobile network some new network elements (nodes) are required, which handle packet-based traffic. The new class of nodes, called GPRS support nodes (GSN), is responsible for the delivery and routing of data packets between an MS and an external packet data network (PDN). More specifically, a serving

Figure 1. GPRS network architecture



GSN (SGSN) is responsible for the delivery of data packets from, and to, an MS within its service area. Its tasks include packet routing and transfer, mobility management, logical link management, and authentication and charging functions. A gateway GSN (GGSN) acts as an interface between the GPRS backbone and an external PDN. It converts the GPRS packets coming from the SGSN into the appropriate packet data protocol (PDP) format (e.g., IP), and forwards them to the corresponding PDN. Similar is the functionality of GGSN in the opposite direction. The communication between GSNs (i.e., SGSN and GGSN) is based on IP tunnels through the use of the GPRS tunneling protocol (GTP) (3GPP TS 09.60, 2002).

GPRS SECURITY ARCHITECTURE

In order to meet security objectives, GPRS employs a set of security mechanisms that constitutes the GPRS security architecture. Most of these mechanisms have been originally designed for GSM, but they have been modified to adapt to the packet-oriented traffic nature and the GPRS network components. The GPRS security architecture, mainly, aims at two goals: (1) to protect the network against unauthorized access, and (2) to protect the privacy of users. It includes the following components (GSM 03.20, 1999):

- Subscriber identity module (SIM)
- Subscriber identity confidentiality
- Subscriber identity authentication

- User data and signaling confidentiality between the MS and the SGSN
- GPRS backbone security

Subscriber Identity Module (SIM)

The subscription of a mobile user to a network is personalized through the use of a smart card named SIM (ETSI TS 100 922, 1999). Each SIM card is unique and related to a user. It has a microcomputer with a processor, ROM, persistent EPROM memory, volatile RAM, and an I/O interface. Its software consists of an operating system, file system, and application programs (e.g., SIM application toolkit). The SIM card is responsible for the authentication of the user by prompting for a code (PIN), the identification of the user to a network through keys, and the protection of user data through cryptography. To achieve these functions it contains a set of security objects including:

- A (4-digit) PIN code, which is used to lock the card preventing misuse;
- A unique permanent identity of the mobile user, named international mobile subscriber identity (IMSI) (3GPP TS 03.03, 2003);
- A secret key, Ki, (128 bit) that is used for authentication; and
- An authentication algorithm (A3) and an algorithm that generates encryption keys (A8) (GSM 03.20, 1999).

Since the SIM card of a GSM/GPRS subscriber contains security critical information, it should be manufactured, provisioned, distributed, and managed in trusted environments.

Subscriber Identity Confidentiality

The subscriber identity confidentiality deals with the privacy of the IMSI and the location of a mobile user. It includes mechanisms for the protection of the permanent identity (IMSI) when it is transferred in signaling messages, as well as measures that preclude the possibility to derive it indirectly from listening to specific information, such as addresses, at the radio path.

The subscriber identity confidentiality is mainly achieved by using a temporary mobile subscriber identity (TMSI) (3GPP TS 03.03, 2003; GSM 03.20, 1999), which identifies the mobile user in both the wireless and wired network segments. The TMSI has a local significance and thus it must be accompanied by the routing area identity (RAI) in order to avoid confusions. The MS and the serving VLR and SGSN only know the relation between the active TMSI and the IMSI. The allocation of a new TMSI corresponds implicitly for the MS to the de-allocation of the previous one. When a new TMSI is allocated to the MS, it is transmitted to it in a ciphered mode. The MS stores the current TMSI and the associated RAI in a non-volatile memory, so that these data are not lost when the MS is switched off.

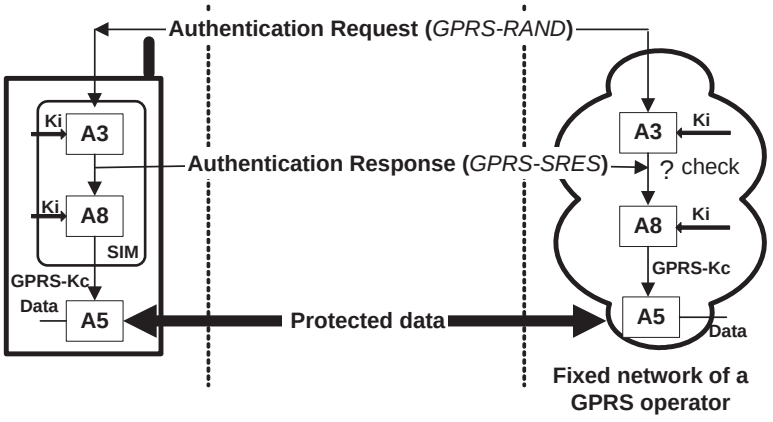
Further to the TMSI, a temporary logical link identity (TLLI) (3GPP TS 03.03, 2003) identifies also a GPRS user on the radio interface of a routing area. Since the TLLI has a local significance, when it is exchanged between the MS and the SGSN, it should be accompanied by the RAI. The TLLI is either derived from the TMSI allocated by the SGSN or built by the MS randomly and thus, provides identity confidentiality. The relationship between the TLLI and the IMSI is only known in the MS and in the SGSN.

Subscriber Identity Authentication

A mobile user that attempts to access the network must first prove his/her identity to it. User authentication (3GPP TS 03.6, 2002) protects against fraudulent use and ensures correct billing. GPRS uses the authentication procedure already defined in GSM with the same algorithms for authentication and generation of encryption key, and the same secret key, Ki, (see Figure 2). However, from the network side, the whole procedure is executed by the SGSN (instead of the BS) and employs a different random number (GPRS-RAND) and thus, it produces a different signed response (GPRS-SRES) and encryption key (GPRS-Kc) than the GSM voice counterpart.

To achieve authentication of a mobile user, the serving SGSN must possess security-related

Figure 2. GPRS authentication



information for the specific user. This information is obtained by requesting the HLR/AuC of the home network that the mobile user is subscribed. It includes a set of authentication vectors, each of which includes a random challenge (GPRS-RAND), the related signed response (GPRS-SRES), and the encryption key (GPRS-Kc) for the specific subscriber. The authentication vectors are produced by the home HLR/AuC using the secret key Ki of the mobile subscriber.

During authentication the SGSN of the serving network sends the random challenge (GPRS-RAND) of a chosen authentication vector to the MS. The latter encrypts the GPRS-RAND by using the A3 hash algorithm, which is implemented in the SIM card, and the secret key, Ki. The first 32 bits of the A3 output are used as a signed response (GPRS-SRES) to the challenge (GPRS-RAND) and are sent back to the network. The SGSN checks if the MS has the correct key, Ki, and, then, the mobile subscriber is recognized as an authorized user. Otherwise, the serving network (SN) rejects the subscriber's access to the system. The remaining 64 bits of the A3 output together with the secret key, Ki, are used as input to the A8 algorithm that produces the GPRS encryption key (GPRS-Kc).

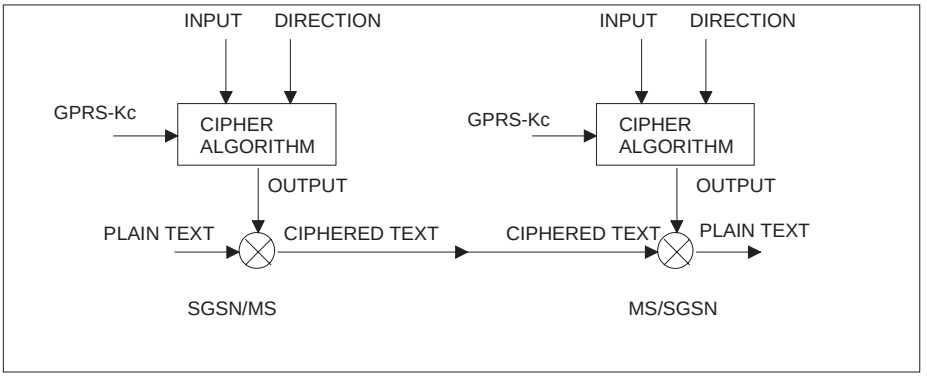
Data and Signalling Protection

User data and signaling protection over the GPRS radio access network is based on the GPRS ciphering algorithm (GPRS-A5) (3GPP TS 01.61, 2001), which is also referred to as GPRS encryption algorithm (GEA) and is similar to the GSM A5. Currently, there are three versions of this algorithm: GEA1, GEA2, and GEA3 (that is actually A5/3), which are not publicly known and thus, it is difficult to perform attacks on them. The MS device (not the SIM-card) performs GEA using the encryption key (GPRS-Kc), since it is a strong algorithm that requires relatively high processing capabilities. From the network side, the serving SGSN performs the ciphering/deciphering functionality protecting signaling and user data over the Um, Abis, and Gb interfaces.

During authentication the MS indicates which version(s) of the GEA supports and the network (SGSN) decides on a mutually acceptable version that will be used. If there is not a commonly accepted algorithm, the network (SGSN) may decide to release the connection. Both the MS and the SGSN must cooperate in order to initiate the ciphering over the radio access network. More specifically, the SGSN indicates whether ciphering should be used or not (which is also a possible option) in the *Authentication Request* message, and the MS starts ciphering after sending the *Authentication Response* message (see Figure 2).

GEA is a symmetric stream cipher algorithm (see Figure 3) that uses three input parameters (GPRS-Kc, INPUT, and DIRECTION) and produces an OUTPUT string, which varies between 5

Figure 3. GPRS ciphering



and 1,600 bytes. GPRS-Kc (64 bits) is the encryption key generated by the GPRS authentication procedure and is never transmitted over the radio interface. The input (INPUT) parameter (32 bits) is used as an additional input so that each frame is ciphered with a different output string. This parameter is calculated from the logical link control (LLC) frame number, a frame counter, and a value supplied by the SGSN called the input offset value (IOV). The IOV is set up during the negotiation of LLC and layer 3 parameters. Finally, the direction bit (DIRECTION) specifies whether the output string is used for upstream or downstream communication.

After the initiation of ciphering, the sender (MS or SGSN) processes (bit-wise XOR) the OUTPUT string with the payload (PLAIN TEXT) to produce the CIPHERED TEXT, which is sent over the radio interface. In the receiving entity (SGSN or MS), the original PLAIN TEXT is obtained by bit-wise XORed the OUTPUT string with the CIPHERED TEXT. When the MS changes SGSN, the encryption parameters (e.g., GPRS-Kc, INPUT) are transferred from the old SGSN to the new SGSN, through the (inter) routing area update procedure in order to guarantee service continuity.

GPRS Backbone Security

The GPRS backbone network includes the fixed network elements and their physical connections that convey user data and signaling information. signaling exchange in GPRS is mainly based on the signaling system 7 (SS7) technology (3GPP TS 09.02, 2004), which does not support any security measure for the GPRS deployment. Similarly, the GTP protocol that is employed for communication between GSNs does not support security. Thus, user data and signaling information in the GPRS backbone network are conveyed in cleartext exposing them to various security threats. In addition, inter-network communications (between different operators) are based on the public Internet, which enables IP spoofing to any malicious third party who gets access to it. In the sequel, the security measures applied to the GPRS backbone network are presented.

The responsibility for security protection of the GPRS backbone as well as inter-network communications belongs to mobile operators. They utilize private IP addressing and network address translation (NAT) (Srisuresh & Holdrege, 1999) to restrict unauthorized access to the GPRS backbone. They may also apply firewalls at the borders of the GPRS backbone network in order to protect it from unauthorized penetrations. Firewalls protect the network by enforcing security policies (e.g., user traffic addressed to a network element is discarded). Using security policies the GPRS operator may ensure that only traffic initiated from the MS and not from the Internet should pass through a firewall. This is done for two reasons: (1) to restrict traffic in order to protect the MS and the network elements from external attacks; and (2) to protect the MS

from receiving unrequested traffic. Unrequested traffic may be unwanted for the mobile subscribers since they pay for the traffic received as well. The GPRS operator may also want to disallow some bandwidth-demanding protocols preventing a group of subscribers to consume so much bandwidth that other subscribers are noticeably affected. In addition, application-level firewalls prevent direct access through the use of proxies for services, which analyze application commands, perform authentication, and keep logs.

Since firewalls do not provide privacy and confidentiality, the virtual private network (VPN) technology (Gleeson, Lin, Heinanen, Armitage, & Malis, 2000) has to complement them to protect data in transit. A VPN is used for the authentication and the authorization of user access to corporate resources, the establishment of secure tunnels between the communicating parties, and the encapsulation and protection of the data transmitted by the network. In current GPRS implementations, pre-configured, static VPNs can be employed to protect data transfer between GPRS network elements (e.g., an SGSN and a GGSN that belong to the same backbone), between different GPRS backbone networks that belong to different mobile operators, or between a GPRS backbone and a remote corporate private network. The border gateway, which resides at the border of the GPRS backbone, is a network element that provides firewall capabilities and also maintains static, pre-configured VPNs to specific peers.

GPRS SECURITY WEAKNESSES

Although GPRS have been designed with security in mind, it presents some essential security weaknesses, which may lead to the realization of security attacks that threaten network operation and data transfer through it. In the following, the most prominent security weaknesses of the GPRS security architecture are briefly presented and analyzed.

Subscriber Identity Confidentiality

A serious weakness of the GPRS security architecture is related to the compromise of the confidentiality of subscriber identity. Specifically, whenever the serving network (VLR or SGSN) cannot associate the TMSI with the IMSI, because of TMSI corruption or database failure, the SGSN should request the MS to identify itself by means of IMSI on the radio path. Furthermore, when the user roams and the new serving network cannot contact the previous (the old serving network) or cannot retrieve the user identity, then, the new serving network should also request the MS to identify itself by means of IMSI on the radio path. This fact may lead an active attacker to pretend to be a new serving network, to which the user has to reveal his/her permanent identity. In addition, in both cases the IMSI that represents the permanent user identity is conveyed in cleartext over the radio interface violating user identity confidentiality.

Subscriber Authentication

The authentication mechanism used in GPRS also exhibits some weak points regarding security. More specifically, the authentication procedure is one way and thus, it does not assure that a mobile user is connected to an authentic serving network. This fact enables active attacks using a false BS identity. An adversary, who has the required equipment, may masquerade as a legitimate network element mediating in the communication between the MS and the authentic BS. This is also facilitated by the absence of a data integrity mechanism on the radio access network of GPRS, which defeats certain network impersonation attacks. The results of this mediation may be the alternation or the interception of signaling information and communication data exchanged.

Another weakness of the GPRS authentication procedure is related to the implementation of the A3 and A8 algorithms, which are often realized in practise using COMP128. COMP128 is a keyed hash function, which uses two 16-byte (128 bits)

inputs and produces a hash output of 12 bytes (96 bits). While the actual specification of COMP128 was never made public, the algorithm has been reverse engineered and cryptanalyzed (Barkan, Biham, & Neller, 2003). Thus, knowing the secret key, Ki, it is feasible for a third party to clone a GSM/GPRS SIM-card, since its specifications are widely available (ETSI TS 100 922, 1999).

The last weakness of the GPRS authentication procedure is related to the network ability of re-using authentication triplets. Each authentication triplet should be used only in one authentication procedure in order to avoid man-in-the-middle and replay attacks. However, this depends on the mobile network operator (home and serving) and cannot be checked by mobile users. When the VLR of a serving network has used an authentication triplet to authenticate an MS, it shall delete the triplet or mark it as used. Thus, each time that the VLR needs to use an authentication triplet, it shall use an unmarked one, in preference to a marked. If there is no unmarked triplet, then the VLR shall request fresh triplets from the home HLR. If fresh triplets cannot be obtained, because of a system failure, the VLR may reuse a marked triplet. Thus, if a single triplet is compromised, a false BS can impersonate a genuine GPRS network to the MS. Moreover, as the false BS has the encryption key, Kc, it will not be necessary for the false BS to suppress encryption on the air interface. As long as the genuine SGSN is using the compromised authentication triplet, an attacker could also impersonate the MS and obtain session calls that are paid by the legitimate subscriber.

Data and Signalling Protection

An important weakness of the GPRS security architecture is related to the fact that the encryption of signalling and user data over the highly exposed radio interface is not mandatory. Some GPRS operators, in certain countries, never switch on encryption in their networks, since the legal framework in these countries do not permit that. Hence, in these cases signaling and data traffic are conveyed in cleartext over the radio path. This situation is becoming even more risky from the fact that the involved end users (humans) are not informed whether their sessions are encrypted or not.

As encryption over the radio interface is optional, the network indicates to the MS whether and which type(s) of encryption it supports in the *authentication request* message, during the GPRS authentication procedure. If encryption is activated, the MS start ciphering after sending the *authentication response* message and the SGSN starts ciphering/deciphering when it receives a valid *authentication response* message from the MS. However, since these two messages are not protected by confidentiality and integrity mechanisms (data integrity is not provided in the GPRS radio interface except for traditional non-cryptographic link layer checksums), an adversary may mediate in the exchange of authentication messages. The results of this mediation might be either the modification of the network and the MS capabilities regarding encryption, or the suppression of encryption over the radio interface.

GPRS Backbone

Based on the analysis of the GPRS security architecture (see the *GPRS security architecture* section) it can be perceived that the GPRS security does not aim at the GPRS backbone and the wire-line connections, but merely at the radio access network and the wireless path. Thus, user data and signaling information conveyed over the GPRS backbone may experience security threats, which degrade the level of security supported by GPRS. In the following, the security weaknesses of the GPRS security architecture that are related to the GPRS backbone network for both signaling and data plane are presented and analyzed.

Signaling Plane

As mentioned previously, the SS7 technology used for signaling exchange in GPRS does not support security protection. Until recently, this was not perceived to be a problem since SS7 networks belonged to a small number of large institutions (telecom operator). However, the rapid deployment of mobile systems and the liberalization of

the telecommunication market have dramatically increased the number of operators (for both fixed and mobile networks) that are interconnected through the SS7 technology. This fact provokes a significant threat to the GPRS network security, since it increases the probability of an adversary to get access to the network or a legitimate operator to act maliciously.

The lack of security measures in the SS7 technology used in GPRS results also in the unprotected exchange of signaling messages between a VLR and a VLR/HLR, or a VLR and other fixed network nodes. Although these messages may include critical information for the mobile subscribers and the networks operation like ciphering keys, authentication data (e.g., authentication triplets), user subscription data (e.g., IMSI), user billing data, network billing data, and so forth, they are conveyed in a cleartext within the serving network as well as between the home network and the serving network. For example, the VLR of a serving network may use the IMSI to request authentication data for a single user from its home network, and the latter forwards them to the requesting VLR without any security measure. Thus, the exchanges of signaling messages, which are based on SS7, may disclose sensitive data of mobile subscribers and networks, since they are conveyed over insecure network connections without security precautions.

Data Plane

Similarly to the signaling plane, the data plane of the GPRS backbone presents significant security weaknesses, since the introduction of IP technology in the GPRS core shifts towards open and easily accessible network architectures. In addition, the data encryption mechanism employed in GPRS does not extend far enough towards the core network, also resulting in a cleartext transmission of user data in it. Thus, a malicious user, which gains access to the network, may either obtain access to sensitive data traffic or provide unauthorized/incorrect information to mobile users and network components. As presented previously, the security protection of users' data in the fixed segment of the GPRS network mainly relies on two independent and complementary technologies, which are not undertaken by GPRS but from the network operators. These technologies include: (1) firewalls that enforce security policies to a GPRS core network that belongs to an operator; and (2) pre-configured VPNs that protect specific network connections.

However, firewalls were originally conceived to address security issues for fixed networks and thus are not seamlessly applicable in mobile networks. They attempt to protect the cleartext transmitted data in the GPRS backbone from external attacks, but they are inadequate against attacks that originate from malicious mobile subscribers as well as from network operator personnel or any other third party that gets access to the GPRS core network. Another vital issue regarding the deployment of firewalls in GPRS has to do with the consequences of mobility. The mobility of a user may imply roaming between networks and operators, which possibly results in the changing of the user address. This fact in conjunction with the static configuration of firewalls may potentially lead to discontinuity of service connectivity for the mobile user. Moreover, in some cases the security value of firewalls is considered limited as they allow direct connection to ports without distinguishing services.

Similarly to firewalls, the VPN technology fails to provide the necessary flexibility required by typical mobile users. Currently, VPNs for GPRS subscribers are established in a static manner between the border gateway of a GPRS network and a remote security gateway of a corporate private network. This fact allows the realization of VPNs only between a security gateway of a large organization and a mobile operator, when a considerable amount of traffic requires protection. Thus, this scheme can provide VPN services neither to individual mobile users that may require on demand VPN establishment, nor to enterprise users that may roam internationally. In addition, static VPNs have to be reconfigured every time the VPN topology or VPN parameters change.

CURRENT RESEARCH ON GPRS SECURITY

The analyzed security weaknesses of the GPRS security architecture increase the risks associated with the usage of GPRS networks influencing their deployment, which realizes the mobile Internet. In order to defeat some of these risks, a set of security improvements to the existing GPRS security architecture may be incorporated. Additionally, some complementary security measures, which have been originally designed for fixed network and aim at enhancing the level of security that GPRS supports, may be applied (Xenakis, 2006). In the following, the specific security improvements and the application of the complementary security measures are briefly presented and analyzed.

SIM Card

The majority of the security weaknesses that are related to a MS and the SIM card of a mobile user have to do with the vulnerabilities of COMP128. To address these, the old version of COMP128 (currently named as COMP128-1) is replaced by two newer versions COMP128-2 and COMP128-3, which defeat the known weaknesses. There is an even newer version COMP128-4, which is based on the 3GPP algorithm MILENAGE that uses advanced encryption standard (AES). In addition, it is mentioned to the GPRS operators that the COMP128 algorithm is only an example algorithm and that every operator should use its own algorithm in order to support an acceptable level of security (Xenakis, 2006).

User Data

User data conveyed over the GPRS backbone and the public Internet most likely remain unprotected (except for the cases that the operator supports pre-established VPNs over the public Internet) and thus are exposed to various threats. The level of protection that GPRS provides to the data exchanged can be improved by employing two security technologies: (1) the application of end-user security, and (2) the establishment of mobile IPsec-based VPN, dynamically. End-user security is applied by using application layer solutions such as the secure sockets layer (SSL) protocol (Gupta & Gupta, 2001). SSL is the default Internet security protocol that provides point-to-point security by establishing a secure channel on top of TCP. It supports server authentication using certificates, data confidentiality, and message integrity. On the other hand, IPsec protects traffic on a per connection basis and thus is independent from the applications that run above it. An IPsec-based VPN is used for the authentication and the authorization of user access to corporate resources, the establishment of secure tunnels between the communicating parties, and the encapsulation and protection of the data transmitted by the network. On-demand VPNs that are tailored to specific security needs are especially useful for GPRS users, which require any-to-any connectivity in an ad hoc fashion. Regarding the deployment of mobile VPNs over the GPRS infrastructure, three alternative security schemes have been proposed: (1) the end-to-end (Xenakis, Gazis, Merakos, 2002), (2) the network-wide (Xenakis, Merakos: IEEE Network, 2002), and (3) the border-based (Xenakis, Merakos: IEEE PIMRC, 2002). These schemes mainly differ in the position where the security functionality is placed within the GPRS network architecture (MS, SGSN, and GGSN), and whether data in transit are ever in cleartext or available to be tapped by outsiders.

Signaling Plane of the GPRS Backbone

The lack of security measures in the signaling plane of the GPRS backbone gives the opportunity to an adversary to retrieve critical information such as the permanent identities of mobile users (IMSI), temporary identities (TMSI, TLLI), location information, authentication triplets (RAND, SRES, Kc), charging and billing data, and so forth. The possession of this information enables an attacker to identify a mobile user, to track his/her location, to decipher the user data transferred over the radio interface, to over bill him/her, and so forth. To address this inability of GPRS, it has been proposed

the incorporation of the network domain security (NDS) features (Xenakis, 2006; Xenakis & Merakos, 2004) into the GPRS security architecture. NDS features, which have been designed for the latter version of UMTS, ensure that signaling exchanges in the backbone network as well as in the whole wire-line network are protected. For signaling transmission in GPRS the SS7 and IP protocol architectures are employed, which incorporate the mobile application part (MAP) (3GPP TS 09.02, 2004) and the GTP protocol (3GPP TS 09.60, 2002), respectively. In NDS both architectures are designed to be protected by standard procedures based on existing cryptographic techniques. Specifically, the IP-based signaling communications will be protected at the network level by means of the well-known IPsec suite (Kent & Atkinson, 1998). On the other hand, the realization of protection for the SS7-based communications will be accomplished at the application layer by employing specific security protocols (Xenakis & Merakos, 2004). However, until now only the MAP protocol from the SS7 architecture is designed to be protected by a new security protocol named MAPsec (3GPP TS 33.200 2002).

CONCLUSION

This chapter has presented the security architecture employed in 2.5G mobile systems focusing on GPRS. This architecture comprises a set of measures that protect the mobile users, the radio access network, the fixed part of the network, and the related data of GPRS. Most of these measures have been originally designed for GSM, but they have been modified to adapt to the packet-oriented traffic nature and the GPRS network components. The operational differences between the application of these measures in GSM and GPRS have been outlined and commented. In addition, the security measures that can be applied by GPRS operators to protect the GPRS backbone network and internetwork communications, which are based on IP, have been explored. Although GPRS has been designed with security in mind, it presents some essential security weaknesses, which may lead to the realization of security attacks that threaten network operations and data transfer through it. These weaknesses are related to: (1) the compromise of the confidentiality of subscriber's identity, since it may be conveyed unprotected over the radio interface; (2) the inability of the authentication mechanism to perform network authentication; (3) the possibility of using COMP128 algorithm (which has been cryptoanalyzed) for A3 and A8 implementations; (4) the ability of reusing authentication triplets; (5) the possibility of suppressing encryption over the radio access network or modifying encryption parameters; and (5) the lack of effective security measures that are able to protect signaling and user data transferred over the GPRS backbone network. To defeat some of these risks, a set of security improvements to the existing GPRS security architecture may be incorporated. Additionally, some complementary security measures, which have been originally designed for fixed network and aim at enhancing the level of security that GPRS supports, may be applied.

ACKNOWLEDGMENT

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KEY TERMS

General Packet Radio Service (GPRS): GPRS is a mobile data service available to users of GSM.

Global System for Mobile Communications (GSM): GSM is the most popular standard for mobile phones in the world.

GPRS Tunneling Protocol (GTP): GTP is an IP-based protocol that carries signaling and user data with the GPRS core network.

International Mobile Subscriber Identity (IMSI): IMSI is a unique number associated with all GSM network mobile phone users.

Second Generation (2G): 2G is a short for second-generation wireless telephone technology.

Second and a Half Generation (2.5G): 2.5G is used to describe 2G systems that have implemented a packet-switched domain in addition to the circuit-switched domain.

Signaling System 7 (SS7): SS7 is a set of telephony signaling protocols which are used to set up the vast majority of the world's public switched telephone network telephone calls.

Subscriber Identity Module (SIM): SIM is a removable smart card for mobile phones that stores network specific information used to authenticate and identify subscribers on the network.

Temporary Mobile Subscriber Identity (TMSI): TMSI is a randomly allocated number that is given to the mobile the moment it is switched on and serves as a temporary identity between the mobile and the network.

Chapter XXIII
End-to-End Security Comparisons Between IEEE 802.16e and 3G Technologies

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ABSTRACT

Security measures of mobile infrastructures have always been important from the early days of the creation of cellular networks. Nowadays, however, the traditional security schemes require a more fundamental approach to cover the entire path from the mobile user to the server. This fundamental approach is so-called end-to-end (E2E) security coverage. The main focus of this chapter is to discuss such architectures for IEEE 802.16e (Mobile-WiMAX) and major third generation (3G) cellular networks. The E2E implementations usually contain a complete set of algorithms, protocol enhancements (mutual identification, authentications, and authorization), including the very large-scale integration (VLSI) implementations. This chapter discusses various proposals at the protocol level.

INTRODUCTION

Mobile-WiMAX (802.16e) is a fourth generation (4G) candidate for mobility and is expected to address many of the current issues we face in 3G technologies. E2E security scheme is one of the major issues, which is currently addressed in variety of forms using IP security (IPsec), secure socket layer (SSL)/transport layer security (TLS), OpenPGP, and S/MIME (Gallop, 2005). The E2E architectures of major 3G technologies including global system for mobile communications (GSM), general packet radio service (GRPS), and code division multiple access (CDMA) and 802.16e will be discussed in this chapter.

The management of the sections is as follows: the next section will discuss details about the ultimate security features attributed to 3G technologies. The GSM section will discuss the security weakness in GSM's initial draft and the E2E solution to overcome its weakness. The fourth and fifth sections talk about GPRS and CDMA respectively. The Mobile-WiMAX section opens the discussion on 802.16e, the candidate for the 4G wireless systems, which contains the security weakness of 802.16e's initial draft and the E2E solution. A thorough comparison and references will be given in the last two sections.

OBJECTIVES OF SECURITY FEATURES FOR 3G/MOBILE-WIMAX

Before discussing security weaknesses of individual 3G technologies, we briefly discuss the objective of 3G security features. These features are (Campbell, Mckunas, Myagmar, Gupta, & Briley, 2002):

- **Mutual authentication:** Authentication is a method to verify that the claimed identity of an entity is genuine. Authentication is a fundamental security service and other necessary services often depend on proper authentication. Many protocols offer a one-way authentication. That is, only the client has to authenticate itself to the server and the server is not required to authenticate itself to the client. A one-way authentication is prone to an attack, so-called; *impersonation*, in which an illegitimate entity could pose as a legitimate one and start a new communication with another legitimate entity or take control an already started conversation. A two-way authentication scheme (mutual authentication) resolves impersonation attack. An E2E security scheme uses a balanced mutual authentication technique. A balanced technique requires equal effort by both entities for authenticate themselves to other entities. This decreases the chance of attacker's success
- **Data integrity:** This guarantees that the data received has not been altered by an unauthorized entity. One method of doing this is through the application of a hash function to the data stream
- **Security between networks:** Networks are interconnected using secure wired links, mainly using IPSec tunneling mechanism.
- **Secure international mobile subscriber identity (IMSI) usage:** The first-time user is assigned an initial IMSI number by the home network.
- **Stronger security scope:** Security is based within the radio network controller (RNC) rather than the base station (BS). An RNC is responsible for controlling and managing the multiple BSs including the utilization of radio network services.
- **User- and mobile-station authentication schemes:** Both user and mobile station share a secret common key, which is called the PIN. This is used for authentication.
- **Secure services:** These services protect the infrastructure against usage and access misuses.
- **Security in applications:** This is critical for mobile-based application security.
- **Fraud detection:** Mechanisms to detect and combat fraud in roaming situations.
- **Flexibility:** As technologies evolve, security features are extended and enhanced as required by new services and threats.
- **Service availability and configurability:** Users are to be notified whether security is on and the available level of security.
- **Multiple cipher and integrity algorithms:** The mobile user and the network negotiate and agree on the best available cipher and integrity algorithms (e.g., KASUMI).
- **Lawful interception:** Mechanisms should be provided to authorize agencies with certain necessary information about subscribers.
- **GSM compatibility:** GSM subscribers should be able to roam in 3G networks and cope with the extended security needed via GSM security context.

Figure 1. GSM system overview (Adapted from Pagliusi, 2002)

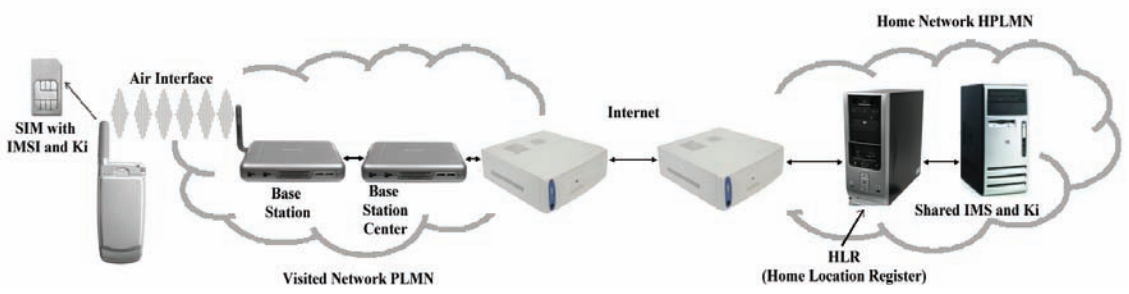


Figure 2: GSM authentication, cipher key generation, and encryption (Adapted from Pagliusi, 2002)

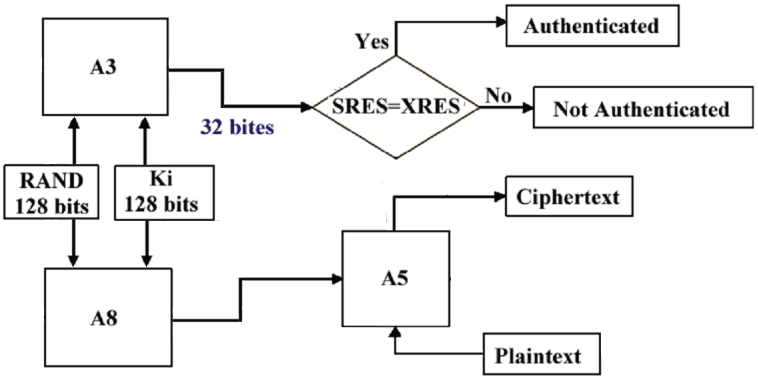
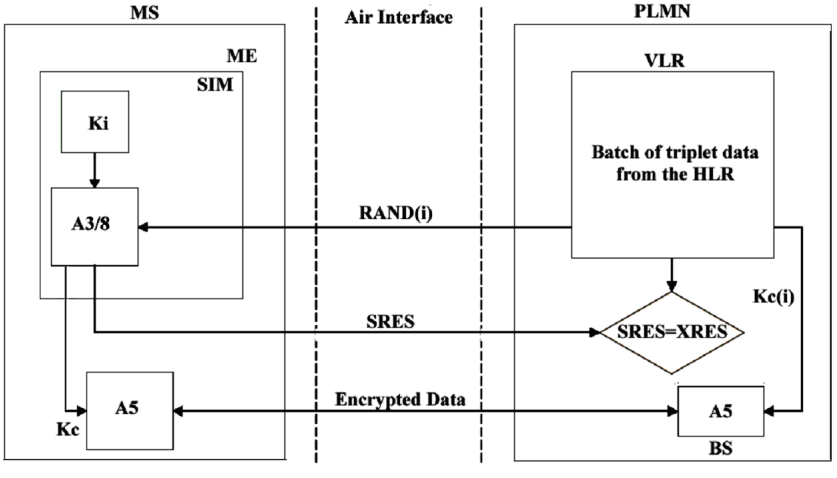


Figure 3. Authentication and encryption in GSM system (Adapted from Pagliusi, 2002)



GSM

In this section, the weaknesses associated to GSM security systems (Pagliusi, 2002) are discussed and the E2E security proposals are considered.

GSM Security Features

Figure 1 shows the GSM system overview. The principles behind GSM security scheme are:

- Subscriber identity confidentiality scheme,
- Subscriber identity authentication scheme (Figure 2),
- Stream ciphering of user traffic and user-related control data schemes; and
- Using subscriber identity module (SIM) as a security module scheme.

Figure 2 shows the GSM authentication scheme in which three algorithms (A3, A5, and A8) are used for authentication, key generation, and encryption. The detailed authentication and encryption schemes for GSM are shown in Figure 3, where A3 (authentication algorithm), A8 (stream cipher), and A5 (key agreement algorithm) are performed in the mobile station and the key is verified in the public land mobile network (PLMN).

GSM Security Attacks

The security attacks associated to GSM architecture are (Pagliusi, 2002):

- **SIM/Mobile Equipment (ME) interface:** The SIM/ME interface is unprotected and can be tapped using an unauthorized device.
- **Attacks on the algorithms A3/A8/(A5/1):** Both A3 and A8 heavily reply on the COMP128 authentication algorithm, which have been cryptanalyzed allowing the recovery of shared master key leading to device cloning. A5/1 has also been attacked by Biryukov and Shamir (Pagliusi, 2002).
- **One-way authentication:** A3 is a one way operator-dependent stream-cipher function. Therefore its functionality suffers from being unbalanced
- **Unprotected signaling:** Though nearly all communications between the MS and the BS are encrypted, however in the fixed networks and between GSM central networks, all the communications and signaling are not protected as they are in plaintext most of the time
- **Attack on SIM card:** Interruption could occur on the operation of the smart card's microprocessor by exposing it to an electronic camera flashbulb. These types of attacks are called *optical fault induction.* Another type of attack, which is performed on the execution of COMP128 table lookups is called *partitioning attacks.*
- **False BS:** GSM provides a unilateral authentication (one-way). Because of the unbalanced nature, this allows attacks (such as man-in-the-middle (MITM) attack) where a malicious third party masquerades as a BS to one or more mobile stations.

E2E Scheme for GSM

The security concerns for GSM could be addressed in an E2E fashion. There are two major concerns in the current GSM structure that prevent the E2E communication, one is the fact that authentication is one way (A3/A8) and the fact that data is exposed and unprotected in certain areas. To prevent these flaws and pave the path to go E2E, a strong user authentication along with complete path encryption are proposed (Aydemir & Selcuk, 2005; Mynttinen, 2000).

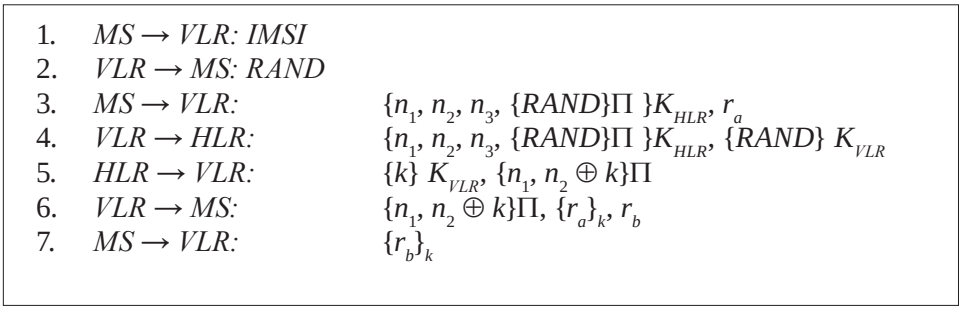
Strong User Authentication

A strong authentication protocol is achieved through user-based rather than device-based. The GSM authentication algorithm contains three fundamental entities in a session (Pagliusi, 2002):

- The mobile subscriber (MS)
- The visiting location register (VLR)
- The home location register (HLR)

The initial draft of GSM states for the authentication scheme to use a cryptographic authentication key embedded in the SIM card of the device. Through the GSM user authentication protocol (GUAP) approach (Aydemir & Selcuk, 2005), the user can authenticate himself/herself through a password instead of the embedded hard-coded key, which breaks the dependency of the SIM card during authentication. The GUAP is based on three entities and in many cases the third entity is a trusted server whose public key is known by

Figure 4. The GUAP scheme (Adapted from Aydemir & Selcuk, 2005)



all parties. GSM doesn't include synchronized clocks, therefore authentication timestamps are not allowed. This can be remedied through the usage of random nonces. According to Figure 4, through VLR, MS is being authenticated to HLR through the usage of the Π password. The HLR public key, K_{HLR}, is known to all parties, and K_{VLR} is the symmetric encryption key shared among the VLR and the HLR. The GUAP protocol is being depicted in Figure 4.

In regards to GSM authentication, the GUAP's main goal is to break SIM card's dependency for added user flexibility. The GUAP's design includes considerations of the MS's computational restrictions. It also includes provisioning of the VLR authentication to both MS and HLR.

E2E Security of Mobile Data in GSM

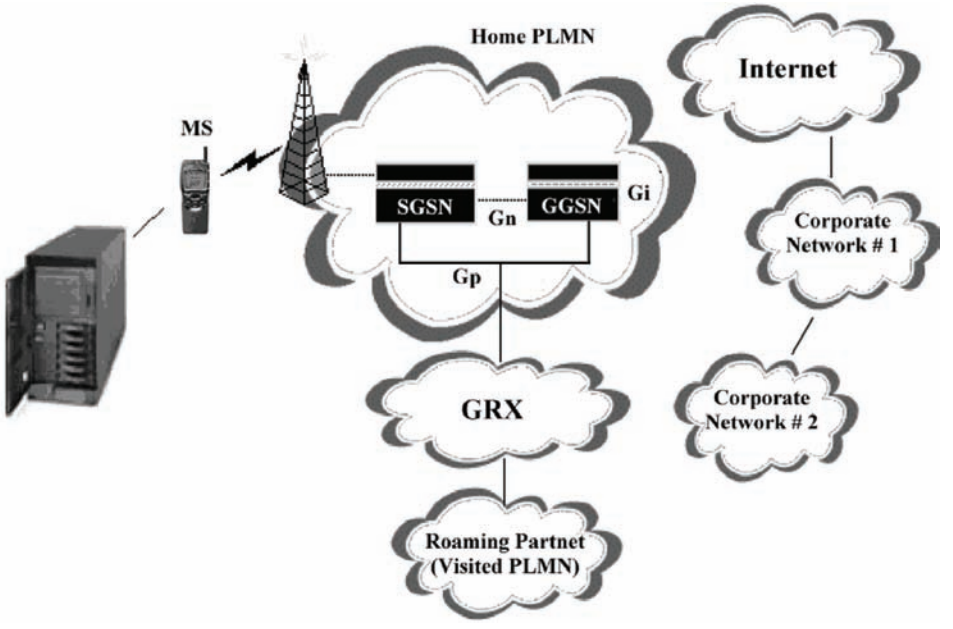
In this approach, the E2E security scheme of mobile data in GSM is considered. It focuses on wireless application protocol (WAP) security, which can be broken. The data path protection in WAP is especially important for voice over IP (VoIP) applications. For this purpose, *WAP Transport Layer E2E Security* is proposed. The E2E security for WAP transport layer is a specification provided by WapForum for supporting WAP E2E security by allowing the WAP clients to establish a straight wireless transport layer security (WTLS) connection with the WAP-based gateway. This gateway no longer encrypts and decrypts the traffic meant for the content-provider's 3rd party. Thus a malicious node is not able to cause problems for the data's confidentiality and integrity. A mechanism, such as; TLS, can be used to provide the required protection. Therefore it is fair to say that the required confidentiality and integrity can be guaranteed. However, non-repudiation property cannot be achieved using this solution. The remedy to this problem, a digital signature can be used in the transaction data, which is able to support integrity and non-repudiation functions. All WAP clients need to have access to digital keys for this to work.

GPRS

GPRS is a data-network-based architecture, which is designed in such a way to integrate well with existing GSM offering MSs “always connected” packet-switched data services. This includes connections to corporate networks and to the Internet. Figure 5 shows a MS logically attached to a serving GPRS support node (SGSN) (“GPRS Security Threats and Solutions,” 2002).The SGSN's main functionality is to provide data services to the MS. Through the GPRS tunneling protocol (GTP), the SGSN can logically be connected to the gateway GPRS support node (GGSN). The GTP provides logical connection among the roaming partners of SGSN and GGSN.

GPRS was introduced as a packet service, which provides E2E IP connectivity with similar security options as in GSM. GPRS uses the same A3/A8 algorithms, which is used in GSM but the randomization function is slightly different. The three GPRS encryption algorithms are GEA1, GEA2, and GEA3, which is A5/3.

Figure 5. GPRS architecture (Adapted from "GPRS Security Threats and Solutions," 2002)



GPRS Classifications of Security Services

Security services provided by GPRS are protections against attacks and providing the following assurances:

- **Integrity:** Integrity is an assurance that data is not altered in an unauthorized manner.
- **Confidentiality:** Confidentiality is protecting data from disclosure to third parties.
- **Authentication:** Authentication provides assurance that all communication parties are really the ones who they claim to be.
- **Authorization:** Authorization is a service, which ensures that only legitimate entities are allowed to take part in any communications.
- **Availability:** Availability means that communication parties and data services are available and usable by any other parties in wireless range.

Data Services Offered on the Gp and Gi Interfaces

Before one can discuss the details about security, it is necessary to discuss the entities related in the data path. There are two main interfaces used in GPRS; *Gp* and *Gi*. G*p* interface is a logical connection among PLMNs. The protocols that deal directly with *Gp* are:

- **GTP:** The logical connection among the roaming partners of SGSN and GGSN.
- **Boarder gateway protocol (BGP):** BGP provides routing for between interfaces.
- **Dynamic name system (DNS):** DNS is a service that translates Internet domain names and computer hostnames to IP addresses.

The GTP provides logical connection among the roaming partners of SGSN and GGSN. If this connection is within the same PLMN, this is called the *Gn* interface. If the connection is between two different PLMNs, then it is known as the *Gp* interface. The G*p* and the G*i* interfaces are the initial and fundamental points of interconnection

between the operator's main network and untrusted external networks.

Threats in GPRS

The following threats are associated to GPRS interfaces:

- **Threats on the *Gp* interface:** The specific threats include attacks on the *availability, authentication, and authorization; integrity; and confidentiality.*
- **Threats on the *Gi* interface:** The same types of threats for *Gp* applied to this interface as well.

GPRS Security Features

The SIM contains the individual subscriber authentication key (ISAK) K*i*, the ciphering key generating algorithm (A8), the authentication algorithm (A3), as well as a PIN. The GEA3 algorithm is implemented in the ME. Figure 6 (Kitsos, Sklavos, & Koufopavlou, 2004), shows the block diagram of the GPRS security in the MS. The key K*i* is 128 bits long.

E2E Security in GPRS

According to Figure 7 (Chang, 2002), the E2E security is shown as a sequential process.

Many of the E2E security options adopted by GSM could be used for GPRS due to the extend of similarities, however the major difference is in the hardware implementation of GEA*i* implementations.

GPRS Security Features.

The main architectural units of the system are based on the RIJNDAEL (Soyjaudah, Hosany, & Jamaloodeen, 2004) and KASUMI (Kitsos, Galanis, & Koufopavlou, 2004) block ciphers. These block cipher architectures meet all the GPRS security needs for an E2E security scheme.

Figure 6. GPRS security block diagram (Adapted from Kitsos, Sklavos, & Koufopavlou, 2004)

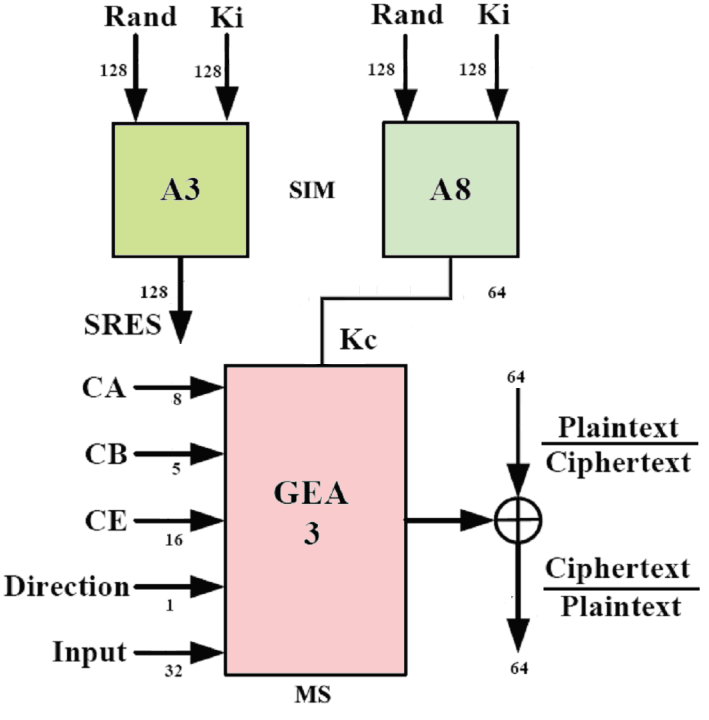
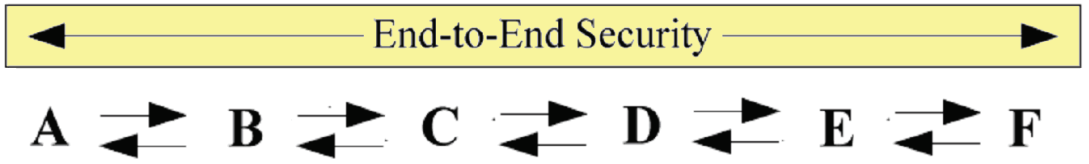


Figure 7: The End-to-End Sequence (Adapted from Chang, 2002)



A. Security of the mobile device
B. Security of the radio path
C. Security of the digital cellular network
D. Security of the GPRS network
E. Security of the public Network
F. Security of the corporate network

CDMA

CDMA ("CDMA End-to-end Security Positioning Paper," 2005) air interface is inherently secure and is superior to many other cellular technologies (i.e., analog and time division multiple access [TDMA] systems). Its security strength comes from the fact that CDMA is a spread spectrum technology that uses Walsh codes.

CDMA uses specific spreading sequences and pseudo-random codes for the forward link (i.e., the downlink from BS to MS) and on the reverse link (i.e., the uplink from MS to BS). CDMA also benefits from a unique and soft handoff capability, which allows an MS to be connected to as many as six radios in a network, each with a unique Walsh code. This means that if anyone attempts to eavesdrop on a subscriber's call, they would have to have several devices connected simultaneously in an attempt to synchronize with all signals, which makes it difficult. Therefore it is difficult for a third party to have a stable link for interception of a CDMA voice channel, even with a complete knowledge of a Walsh code. Synchronization is a critical part, since without this synchronization the listener would only hear noise.

The 1x evolution-data optimized (1xEV-DO) version of CDMA was developed by Qualcomm in 1999. This version offered a bandwidth of greater than 2-Mbit/s for downlink stationary communication. The term 1xEV-DO also refers to the fact of being a direct evolution of the 1x (1xRTT) air interface standard, with its channels carrying only data traffic.

Compared to the GPRS and GSM networks, the 1xEV-DO feature of CDMA2000 networks is significantly faster and provides access terminals with air interface speeds of up to 2.4576 Mb/s and 3.1 Mb/s.

1xEV-DO has inherent security that protects the identity of users and makes interception very difficult. In addition, the Media Access Control Identification (MACID), which is assigned to users, is encrypted. Every user packet is assigned a variable time slot and the data rate for all users is controlled by the access terminal based on the radio conditions. Packets are divided into sub-packets using hybrid automatic repeat request (HARQ) and early termination mechanisms. These mechanisms make it virtually impossible to identify the user or correlate user packets. 1xEV-DO standard specification includes the possibility of supporting a security protocol layer suitable for future security implementation.

E2E security. CDMA ("CDMA End-to-end Security Positioning Paper," 2005) supports a number of security features such as OS hardening (file-system security); user access and operation audit; centralized authentication; user profile and group management; privilege-based user groups;

customer authentication; and secure remote access with IP Security Protocol (IPSec). Specific steps in the E2E security follow.

Subscriber Authentication

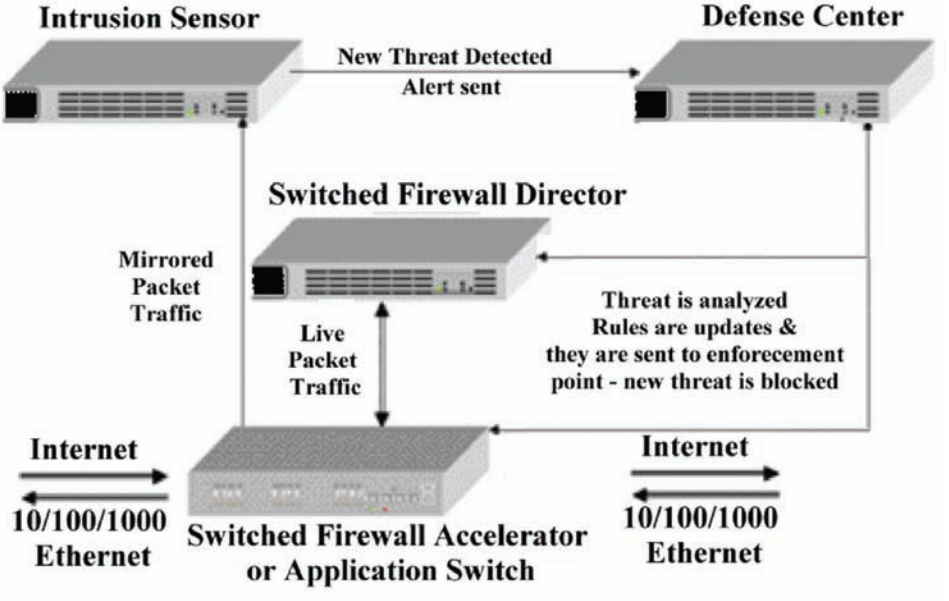
The key feature control mechanism is to protect the infrastructure and to prevent unauthorized access to network resources. The CDMA's access authentication is performed via an 18-bit authentication signature, which is verified via the user information of the network's database, the HLR and authentication center. CDMA is equipped with over the air service provisioning (OTASP), which is the ability of the signal's carrier to add new types of services to a customer's handset and provision it via wireless network instead of requiring the customer to bring the phone to a carrier's location for reprogramming. The 1xEV-DO uses the same 512-bit algorithm in OTASP for exchanging keys among the mobile device and the access node-authentication authorization accounting (AN-AAA) server. Users are authenticated through the usage of the challenge handshake authentication protocol (CHAP) via the packet data serving node-authentication authorization accounting (PDSN-AAA) server. CHAP is a strong Internet authentication protocol that is leveraged in the wireless network to verify identity.

Packet Core

In CDMA architecture, the packet data network supports:

- **Subscriber stateful firewall (SSF):** SSF protects both subscriber or operator's infrastructure traffic
- **Ingress anti-spoofing (IAS):** IAS prevents any malicious entity from launching attacks based on forged source IP addresses.
- **Filters and virus protection services:** Protects servers from viral infections.

Figure 8. Nortel's threat protection system (TPS) (Adapted from "CDMA end-to-end security; Positioning paper," 2005)



- **Layered protection:** TCP/IP layer to application layer deep packet filtering and inspection.
- **On-board lawful intercept:** For meeting regulatory security requirements
- **Traffic steering:** Services, such as; content filtering and server protections against malicious software.
- **Deep packet inspection:** Including application layers down to TCP/IP layer.

Transport Security (Protecting Traffic in Transit)

This is for protecting the MS or in a layered-security defense mechanism. This offers coverage on virtual private network (VPN) protocols, IPSec, and secure socket layer (SSL). IPSec VPN provides encryption, authentication protection at the IP layer, which protects all IP application/data traffic. SSL VPN provides secure communications for the Web application. Nortel Networks claims to be the first vendor to offer support for both VPN technologies in a single and unique platform. SSL VPNs provide security above the TCP/IP layer, thus ensuring compatibility with existing network address translation (NAT) services and other firewall configurations and proxy settings.

Perimeter Security (PS)

According to Figure 8, Nortel Networks claims to have introduced the threat protection system (TPS) using Snort-based™ intrusion detection system, which is complex but easy to use. This is based on the Perimeter security systems, which have been around for quite some time and are generally referred to as a firewall.

A rule-based, deep-packet inspection method is the heart of the TPS Intrusion Sensor, which examines the protocol and data fields on the incoming packets and checks for possible attack patterns. The sensors are capable of detecting anomalies such as: IP stack fingerprinting, port scan, denial of service (DoS) attack and address resolution protocol (ARP) spoofing. The incoming back packets are analyzed to pin-point threats. This is done at the Defense Center and rules updates are automatically transmitted real-time to firewalls for blocking new detected threat. The Defense Center provides threat analysis along with policy management and control. It also includes: traps and trace capabilities, reports, and event database. It also supports a centralized management for hierarchical sensors grouping.

End Point Compliance

End points, either MS, BS, or the management consoles could be potential sources of threats. These end-points may be infected with viruses or worms, which in case they are allowed to connect to the wireless network, may become the source of an attack. Unprotected end points can carry DoS or distributed DoS attacks. Nortel VPN Tunnel Guard is said to provide a security solution capable of enforcing on both managed (IPSec/SSL) and unmanaged SSL endpoints.

MOBILE-WIMAX (IEEE 802.16E)

Mobile-WiMAX was introduced in 2004 and it is designed to cover a 10-mile range for a data bandwidth of up to 15 MBps. Mobile-WiMAX's security mechanisms claim to have covered the holes in Wi-Fi. These security measures include ("Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems," 2004):

- **Data over cable service interface specification for baseline privacy +interface (DOCSIS BPI+)** for the interoperability equipment certification and device data privacy
- **Privacy key management for extensible authentication protocol (PKM-EAP)**, which is one of the requirements for an E2E authentication using TLS.
- **Counter mode with cipher block chaining message authentication code protocol (CCMP):** Used for encryption using Advanced Encryption Standard (AES) and 3 Data Encryption Standard (DES).

Through PKM-EAP, a mechanism is provided by which both BS and MSS (Mobile Subscriber Station) can mutually be authenticated and can establish a shared secret, which is called the "AAA-key". For completing the EAP-based authentication integration into the 802.16e's protocol, the following terms have to be defined ("Secure Association Establishment for PKM-EAP" 2004), : (1) PKM authorization key (AK) establishment and installation, (2) MSS static Security Association provisioning,and, (3) Ciphersuite signalling.

E2E Security Enhancements

The heart of the authentication protocol for Mobile-WiMAX is around the PKMv1. The only issue about PKMv1 is that it offers a one-way authentication. The PKMv1 protocol integrates AK and traffic encryption Key (TEK) exchange processes. Two nodes perform authorization process with one another in a one-way fashion, that is, one node only sends the authorization signal to the other node. If authorized and authenticated, the ACK (acknowledgement) signal is sent back and they are allowed to communicate. Together with the ACK, the authorizing node provides the node with the information of security associations (SAs) in which the node is authorized to access. This suffers from variety of attacks, which are described shortly.

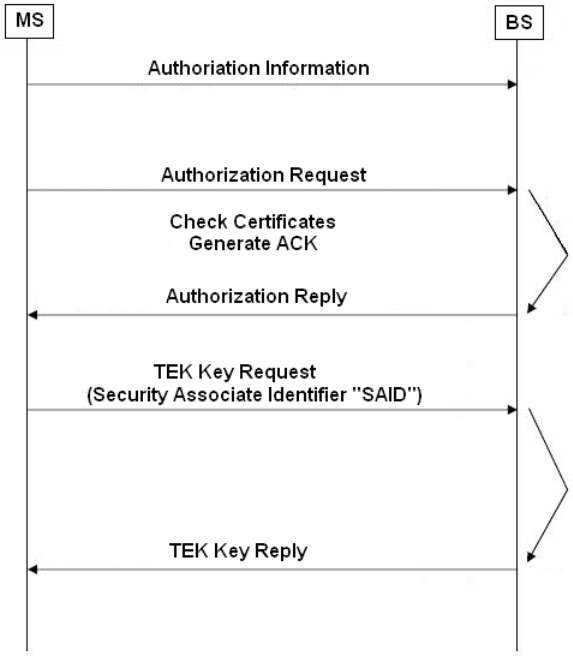
To correct this issue, PKMv2 is deployed. This has been shown in Figure 9 (Johnston, 2003). The issues with a one-way authentication are (Puthenkulam, Mandin, 2003) :

- It is prone to false BS attacks (base impersonation).
- It is also prone to MITM attacks.
- It only works when providers control all the devices.

Other security enhancements required for an E2E scheme are:

- **Bi-directional certification exchange:** In order to achieve an E2E security scheme, a

Figure 9. Private key management version 2 (Adapted from Johnston, 2003)



bi-directional certificate exchange for mutual authorization is required. This is achieved by Rivest-Shamir-Adleman (RSA)-based mutual authorization based on PKMv2.

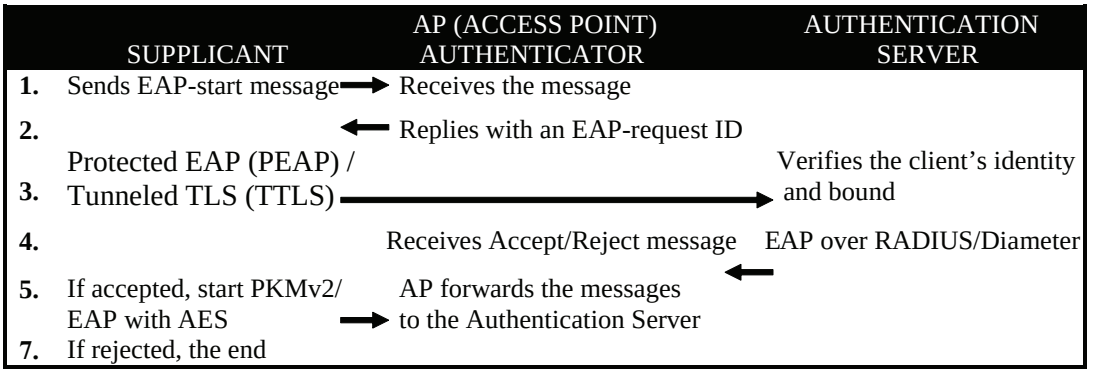
- **Support of key hierarchy:** To support key hierarchy, Temporary Key Integrity Protocol (TKIP) is used through utilization of the master key (MK) and the pairwise master key (PMK) schemes.
- **PKM and EAP messages protections:** EAP has been known to cure security vulnerabilities, such as in the lack of user identity protection and MITM attack. This requires enabling encryption and utilizing PKM EAP messages for user authentication. To fix the previous problems, PKM messages should be bi-directional and EAP messages should use a four-way handshaking scheme
- **Weakness in the X.509 certificates:** X.509 certificate has the following issues:
    - Is restricted to certain business model and flexibility is a major issue.
    - Does not support user-based identity authentication, due to the fact that devices and services are greatly coupled, and
    - Trusting a certificate authority (CA) could become a source of a new attack.
- **Poor IV construction:** Initialization vectors (IVs) often use similar and repetitive structures. Through traffic pattern analysis, IVs can easily be known and broken. to remedy this, more complex IV structures with high key-bits (at least 128-bites) is the remedy to this problem.
- **802.16 key exchange issues:** A 2-key 3DES based key wrap is currently the standard of the initial draft for TEK exchange, which is not as strong (82bits) as the TEK keys (128 bits) it carries. There should be a mechanism to ensure that TEKs do not repeat for frequent exchange of TEKs. This could suffer from replay attacks, since there is no liveliness in the key exchange protocol and it also suffers from MITM attacks. Adding EAP-TLS authentication framework and the AES-CCM cipher suit will solve the problem.
- **Security improvements suggestions:** As a summary, the following security improvements are suggested for Mobile-WiMAX (as well as 802.16d):
    - PKM requires mutual authentication (PKMv2), necessary protections against reply and a stronger than DES-CBC cipher suite.
    - Deployment models should include additional security features for performance related issues (fast roaming, etc).
    - The current security models and solutions are not able to fully utilize the core network AAA infra structures due to the very low PKI support.
    - A single X.509 credential has limitations. To overcome this, it's recommended to use a flexible protocol, such as EAP, which supports multiple user credentials.
    - A scalable security solution is required to be deployed into the existing architecture and infrastructure for 802.16e requirements.

E2E Security Architecture

Figure 10 conceptually displays a client-server-based (i.e., VoIP) E2E AAA on 802.16 networks offering portability and fully mobile operations. The architecture is built around the three-party protocol (PKM v2), as defined in 802.16e (Agis et al., 2004).

Figure 10 shows that the over-the-air security association (authentication and encryption) is established through the PKM-EAP protocol. This is a complete client/server architecture, where EAP carries the AAA backend connectivity using Radius or Diameter. EAP offers a strong support for key-driven cipher mechanisms (i.e., EAP-MSCHAPv2 and EAP-AKA). It is also recommended to use an E2E tunneling protocol such as protected EAP

Figure 10. 802.16 E2E security framework



(PEAP) or tunneled TLS (TTLS) for the purpose of mutual authentication and a 128-bit or better TLS encryption method to further fortify the E2E security strength(particularly where weaker EAP methods may be deployed).

CONCLUSION

In this chapter, E2E security schemes were discussed for 3G technologies; GSM, GPRS, and CDMA and for Mobile-WiMAX (802.16e). The weaknesses of the initial drafts were pointed out and different enhancements were suggested. In most cases, mutual authentication as well as strong algorithms for authentication and authorization solved the E2E problems.

Comparing the performance issue, GSM systems have been around for a while and the designed architecture had not taken much security into account due to the security issues not being severe at the time. However as the technology matured, the newer technologies integrated more security aspects in their initial drafts, such as in CDMA. Now Mobile-WiMAX is expected to overcome all security issues and develop a full-scale E2E architecture with high performance E2E availability and security options. The encryption/authentication/authorization strengths of EAP/TLS/CCMP/PKM are unbeatable.

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KEY TERMS

Authentication, Authorization, and Accounting (AAA): AAA is an access control scheme, overseeing the auditing framework and policy enforcement for commercial access and computing systems.

Code Division Multiple Access (CDMA): CDMA is also a 2.5G technology offering codes for multiplexing various cell calls. Therefore it does not divide the channel into time slots (time domain multiple access [TDMA]) or frequency bands (frequency division multiple access [FDMA]). Instead, CDMA encodes data with codes associated with every channel; therefore they do not have any overlaps in time or frequency bands. CDMA is a major improvement in cellular technologies.

Customer-Premises Equipment (CPE): End communication device that local subscribers communicate to. Through CPE, the information transmitted to and from all local subscribers are transmitted back to the centre.

End-to-End (E2E): E2E security covers the system's security functionality and performance from one end to the other and back.

General Packet Radio Service (GPRS): GPRS is an extension to GSM technology, which offers higher data rates compared to GSM. GPRS is considered a 2.5G technology.

Global System for Mobile Communications (GSM): GSM is the most popular standard and one of the oldest technologies still used for cellular networks throughout the world. GSM is considered a 2G cellular technology with digital integration.

Initialization Vector (IV): IV is a block of bit streams that is attached to every security data to produce a unique and independent stream for encryption.

Mobile Subsciber Station (MSS) = Mobile Station (MS): These are end-user devices.

Pairwise Master Key (PMK): PMK is used in peer-to-peer communication schemes for sharing a master key that would last the entire session. This is mainly used for data encryption and integrity.

Privacy Key Management (PKM): PKM is a private key scheme used with EAP and TLS for providing E2E security schemes for wireless technologies.

Third and Fourth Generation (3G/4G): 3G/4G cellular networks are used in the context of mobile standards. The services associated with 3G are capable of transferring both voice and non-voice data simultaneously. Though not official yet, the 4G, however, will be fully IP-based converging wired and wireless access technologies. It is expected to reach bandwidth within a few hundred mega bit per second offering E2E QoS.[1]

Transport Layer Security (TLS): TLS is used mostly in client/server applications, which require endpoint authentication and communications privacy, particularly over the Internet. This is mostly done using cryptographic measures.

Virtual Private Network (VPN): VPN is a communications tunnel uses a pre-existing (and often unsecure, such as the Internet) network to connect a remote user to a corporate network. The information is tunneled, encapsulated, and encrypted when passes through the unsecure network. Once the information reaches the destination, it is decapsulated and decrypted.

Worldwide Interoperability for Microwave Access (WiMAX): WiMAX, which has been defined by the WiMAX Forum, formed in 2001. WiMAX is also known as IEEE 802.16 standard, officially titled; WirelessMAN and is an alternative to DSL (802.16d) and cellular access (802.16e).

ENDNOTE

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Chapter XXIV
Generic Application Security in Current and Future Networks

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ABSTRACT

This chapter outlines how cellular authentication can be utilized for generic application security. It describes the basic concept of the generic bootstrapping architecture (GBA) that was defined by the 3rd generation partnership project (3GPP) for current networks and outlines the latest developments for future networks.The chapter will provide an overview of the latest technology trends in the area of generic application security.

INTRODUCTION

Applications in wireless networks require a very reliable method for user authentication and communication security. We will outline the reason for the security needs for mobile application compared to Internet application security. It starts with the application specific security approach used today by many mobile operators and describes the motivation that lead into the development of the generic bootstrapping architecture (GBA) of 3rd generation partnership project (3GPP).

The main function of GBA and also its dialects and variations are explained. GBA has been adopted by various standardization bodies and used by many applications. GBA was first embraced by mobile applications, like the 3GPP Mobile Broadcast Multicast Service, open mobile alliance (OMA) presence service, OMA broadcast smart card service protection profile, GBA Profile, and so forth.

The ongoing convergence of fixed and mobile network resulted in the adaptation of GBA-based application security for fixed and cable networks. We close with a snapshot of the ongoing work for

application security in beyond third generation (B3G) networks.

APPLICATION SECURITY FOUNDATIONS IN MOBILE NETWORKS

Special Requirements for Mobile Application Security

Applications in wireless networks require a very reliable method for user authentication and communication security due to their special environment. There are the following security reasons for this:

- The communication to the service provider goes over the air and can be eavesdropped or modified, if not properly secured.
- The service may be offered over any kind of IP-based channel, then the protection of the service by the underlying bearer protocol can not be taken for granted. The authentication and the service usage may be performed over different channels.
- Username/password authentication is not very secure or user friendly on a mobile device with numeric keypad; hence the temptation to choose too short or easy-to-write passwords is even greater than in the fixed network environment.

Operators or third parties that provide server-based applications in mobile networks have to face additional challenges that reflect on the choice of a potential security solution for application security:

- **Roaming agreements:** The home operator of a user maybe liable to roaming partners or application providers, if an unauthorized user uses a service. This potential liability could even be exploited by malicious application providers. This is no empty threat, as the malicious usage of premium short message service (SMS) usage is an existing problem.
- **Development costs:** Development of mobile applications is much more expensive than that for Internet usage, hence if an application is seriously compromised, then the resulting loss is much higher.
- **Updating problem:** In the fixed network environment security patches and updates are a daily occurrence, this is not that common in the mobile environment. Even if some mobile software platforms offer the possibility to be updated via a PC or over-the-air (OTA) mechanisms.
- **Protection of investments:** Mobile operators make big investments in their network infrastructure; hence reusage of deployed network nodes needs to be taken into account. Especially, when new services are rolled out, these services should work in a harmonic way with the existing nodes.
- **Existing smart card base:** Operators hand out smart cards to their subscribers, these cards have very different capabilities (e.g., subscriber identity module (SIM) cards, universal SIM [USIM], etc.), and operators are unlikely to replace already handed out smart cards. It is more likely, that the user replaces the device. A smart card is replaced, when a user changes operators.
- **Service usage costs:** The cost of browsing is bound to the type of access the user is using. When mobile access is used, this may imply some significant costs for the user. Also, some mobile service fees already include the access cost, that is, the user does not have to pay twice for the content and the delivery. Hence, user authentication comes in mobile applications "earlier" than in the Internet case.
- **Reliability and availability:** If an Internet application does not work, because the authentication database crashed, then in many cases this is not that severe an issue and the user can still use other services (except for those 100% online shops like amazon.com). But if the operator's subscriber database can not be reached, users can not make phone calls, roam, send SMS messages, and, in the end, the operator has no opportunity to offer

any kind of service and obtain revenue. The availability and reliability requirements for mobile network nodes are very high.

- **Scalability:** Scalability of mobile networks security solutions is a critical factor. Solutions are standardized on a global level, for example, for small local operators, as well as for large international operators. Hence, solutions have to work also for millions of people at the same time and it must be possible to extend them gradually depending on the growing subscriber basis. Usage scenarios and scalability requirements, where a whole full soccer arena at once requests one service server and still the service should work and start on time, are not unusual.
- **Convergence:** For operators that run both fixed and mobile networks the issue of convergence gains importance, since it allows a more flexible re-use of the network backend servers and functions.

When the first mobile applications started after voice and SMS the requirements for a more generic application security were not clear. This resulted in a fast to roll-out, but with less generic approach as will be explained next.

Historic Approaches to Application Security

Application nodes in mobile networks in the past tend to have a monolithic security solution that is highly customized to the individual application. This has to do with the fact, that operators like to buy their equipment from various vendors, and re-usage and extensions of existing infrastructure requires standardized interfaces. This standardization takes quite some time and that backward compatibility and integration with the existing nodes is a big challenge. Another argument for having customized security solution was that there were not that many new applications were not expected to come with a fast pace. For application security the return of investment was also an important consideration. The system had first to attract some subscribers and be accepted, before an expensive security solution of higher quality is considered, that is, why spend a lot of money, if it will not be used. This subsection describes how application security is often managed today and how it was managed in the past and what are the problems related to it:

- **Voice:** The terminal authenticates to the network utilizing a shared secret stored in the smart card and the operator's subscriber database. For application security needs, the *authentication vectors* (AVs) are distributed to the corresponding nodes.
- **Early IP multimedia subsystem security (IMS):** The 3GPP early IMS security solution of Release 6 (3GPP, TR33.978, Release 6) uses IP address binding, that is, the IP address assigned by the gateway GPRS support node (GGSN) is used for subsequent user authentication to the IMS service.
- **IMS:** The IMS security is bound to the credentials of the IMS SIM (ISIM) application on the universal integrated circuit card (UICC) smart card and these credentials are used by the mobile terminal for authentication to the IMS network. This is outlined by 3GPP (TS 33.203,Release 6). The user authentication is delegated from the operator's subscriber database towards the IMS network (i.e., the serving call-session-control-function [S-CSCF]).

The first mobile application was voice and few people envisioned the further usage mobile networks would get and were surprised by the popularity of SMS. 3GPP IMS with its wide range of service possibilities has security wise two flavors: (1) IP address binding, which comes quite inexpensive to mobile operators, and (2) the full IMS security, which requires that the subscriber is equipped with a new smart card that contains an ISIM application on it. The early IMS security solution has its cost-wise advantages and allows a roll-out and provisioning of the service also to subscribers with "old" smart cards, but the usage of monolithic and application specific security solutions cause some problems. Additionally, the direct usage of AVs in applications causes some

general problems that require a more generic approach. The specific and general issues are listed as follows:

- **Fraud potential:** With the convergence of networks IP address spoofing may become a threat for application specific solutions that utilize IP address binding.
- **Scalability:** The IP address binding solution is not very well scalable for large networks and large amounts of simultaneous service-users. It is difficult to scale for many application scenarios in diverse future networks, where users may roam between network types.
- **Performance and dependability:** The backbone subscriber database, that is, the home subscriber server (HSS) or the home location register-authentication center (HLR-AuC) should not be contacted too often to obtain fresh user credentials, since these databases are very large and if this database is going down due to overload requests from application servers, then the operator can not even offer simple voice calls.
- **Synchronization problems:** If a new application utilizes the smart card based authentication, then they consume AVs from the HSS/HLR-AuC. This can lead to sequence number synchronization problems, which becomes more severe when the number of services increases.
- **User experience:** Different user authentication methods often result in bad user experience and difficulties for the help-desk if the authentication fails for unknown reasons.
- **Combined networks:** If an operator has broadband fixed network access and mobile networks, then the broadband subscriber may not have the ISIM or the IP address assigned from the GGSN.
- **Future proof:** New applications need new security solutions. If the network is structured in separate monolithic pillars, then the re-usage of the existing infrastructure for security is very difficult without modifying the already deployed infrastructure. Since in telecommunication availability is a critical factor, the modification of well-running systems is a very sensitive issue.

There were some early non-standardized approaches to re-use the existing authentication infrastructure of an operator for general application specific security (Gerstenberger, Lahaije, & Schuba, 2004). The aforementioned issues lead in 3GPP and 3GPP2 to the standardization of the GBA.

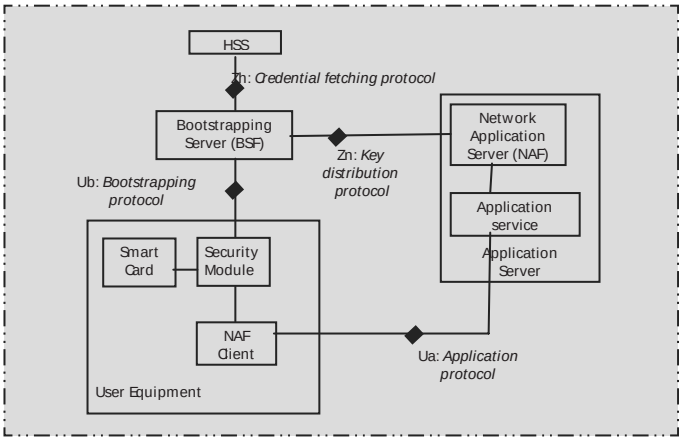
Generic Bootstrapping Architecture (GBA)

We will now introduce the GBA nodes, the provided functionality, and the interworking. The main goal of GBA is to provide a common shared secret to an application server and a mobile terminal based on the cellular authentication, the details of this protocol are described in the 3GPP technical specification (3GPP TS 33.220, Release 6) and we will focus on this aspect.

The application. The basic setting is that we have an application server that offers services to the user. The application service does not need necessarily to be part of the operator's network. There is a general trend to outsource the application services to external parties and just take selected services into the "operator portal." This service should now be secured using the mobile smart card credentials and hence the existing trust relationship between the user and the operator. For this purpose, the service provider needs to have an agreement with the home operator of the user. This application server has two subcomponents, one that takes care of fetching credentials from the user's home network and is called network application function (NAF) in GBA and then the actual application itself that uses the credentials to secure the communication with the mobile terminal, which we call application service.

The terminal. A 3GPP terminal is called user equipment (UE). In strict 3GPP terms it has two components, the smart card (UICC) and the mobile equipment (ME). We will refine this model slightly, by also distinguishing between the device platform and the application in the terminal. The

Figure 1. Generic bootstrapping architecture



UE can authenticate with the network using cellular second generation (2G) or 3G-based authentication protocols. The intention is to reuse the authentication mechanism for the application communication security. Hence, we have a *security module* (see Figure 1) that communicates with the smart card and the so-called bootstrapping server function (BSF). Then there is the actual client application (NAF client) that communicates with the application server (NAF server) in the network, and uses the application specific keys.

The smart card. 3GPP Release 6 and Release 7 GBA assume the existence of a UICC. The UICC contains an ISIM and/or USIM application. If the operator wishes that the application is really closely bound with the smart card, then he/she can utilize the so-called GBA aware smart card (GBA_U), where the application specific key generation and part of the storage is performed in the UICC. GBA can be used also with SIM cards. This 2G GBA was introduced in Release 7 in the 3GPP technical report (3GPP TR 33.920, Release 7) due to the large market need to allow operators to utilize the existing smart card infrastructure without being forced to hand out immediately new smart cards to the user to use GBA-based services.

The network. The heart of the network is the operators subscriber database the HSS, respectively the HLR with accompanied AuC. This huge database is used to store the subscriber data including the counterpart of the credentials (i.e., master key) stored in the smart card that is handed out to the user and resides in the mobile terminal. This database provides the basic key material (i.e., authentication vector) to the BSF that is under mobile network operator control. This server can be seen as a credential server. Once the user is properly authenticated the BSF generates the application specific keys which are handed out to the application server, that is, the NAF.

The GBA system entities need to interact with each other to provision the application in the terminal and the application server with a shared secret that can then be utilized for various security purposes:

- **Bootstrapping interface (Ub):** The mobile terminal contacts the BSF and authenticates via authentication and key agreement (AKA) and triggers the key generation in the BSF. This interface is called Ub interface and defined in the 3GPP technical specification (3GPP TS 24.109, Release 6).
- **Credential fetching interface (Zh):** The application specific credentials are based on the mobile credentials stored in the subscriber database HSS of the operator. Therefore the BSF needs to obtain the AV to be able to establish an authentication session between the mobile terminal and the BSF and derive

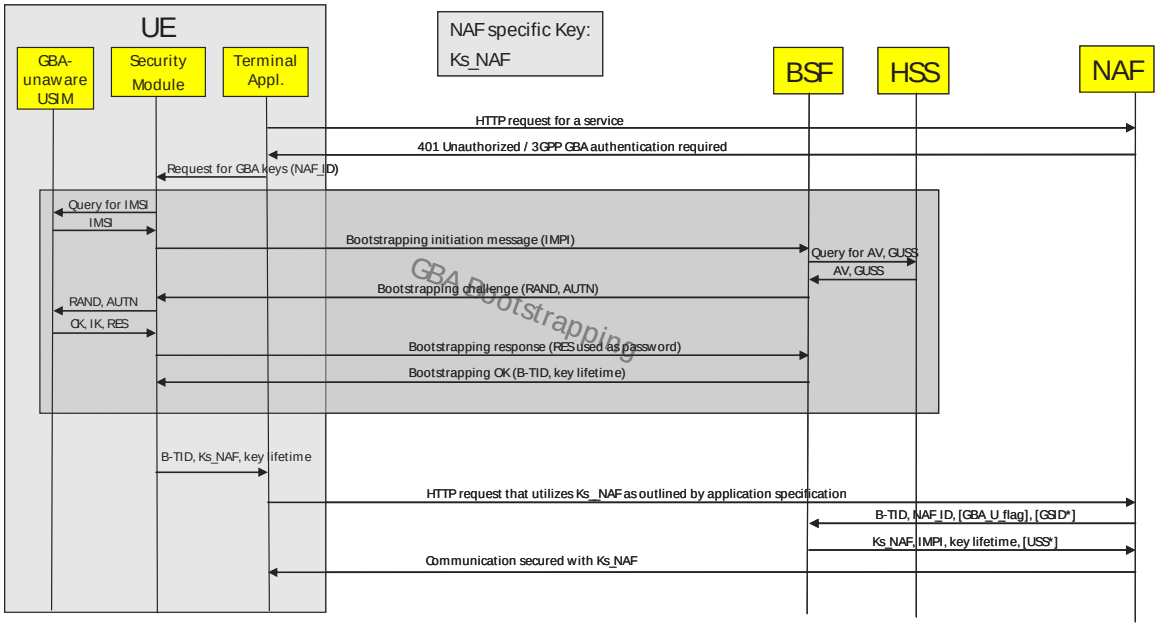
further application specific keys. Also, some operator policies in the form of GBA user security settings (GUSS) can be stored in the HSS and passed to the BSF over this interface. The GUSS can contain application specific USSs and additionally BSF-specific guidance information, like user-specific key lifetimes, and UICC type of the user. The credential interface is defined as Zh interface and specified in the 3GPP technical specification (3GPP TS 29.109, Release 6). This interface is operator internal and specified as being Diameter based (Calhoun, Loughney, Guttman, Zorn, & Arkko, 2003) by the Internet Engineering Task Force (IETF), but since many operators have highly customized HLR/HSS it can be expected that operator-specific adjustments will be made (but likely not standardized).

- **Key distribution interface (Zn):** The application server has a library or a "plug-in" that requests the application-specific credentials, credential-related data, and USS from the credential server (BSF). This key distribution interface in 3GPP Release 6 Diameter based and called Zn interface. In Release 7, an alternative method was specified to support Web services (WS)-based protocol as this makes it easier for application developers to communicate with the credential server. Both implementations of the Zn interface are defined in the 3GPP technical specification (3GPP TS 29.109, Release 7).
- **Application interface (Ua):** The application-specific interface is called Ua interface and specified in (3GPP TS 24.109, 2006). The details of the actual protocol used in the Ua interface depend on the actual use case, for example, browsing, streaming, and so forth. The derived application-specific credentials will be used to secure the communication of this interface, how this is done, is application specific and defined in the application-specific specifications, for example, 3GPP multimedia broadcast/multicast service (MBMS) technical specification (3GPP TS 33.246, Release 6).

The actual application-specific key generation consists of the following basic steps:

1. The user wishes to use a service. The application server wishes to utilize GBA to secure the communication to the terminal. Hence, the terminal is requested to use GBA. This information (i.e., whether GBA needs to be used) can be pre-configured to the NAF client, or the application server may indicate over Ua interface that GBA should be used.
2. The NAF client triggers the security module in the terminal to bootstrap with the BSF utilizing AKA over the Ub bootstrapping interface.
3. The BSF then utilizes the Zh interface to fetch the needed data for the creation of the master session key. The BSF derives the master session key. Based on this master session key NAF specific application keys are derived when a specific NAF requests it over Zn interface later on. (Depending on the GBA type used, one or two application specific keys are derived.)
4. The resulting master session key and transaction ID are stored in BSF server. The security module in terminal also derives the master session key by contacting the smart card. The master session key and the transaction ID are stored in the security module. Note, that here are small differences between the different GBA types. Based on this master session key, NAF-specific application keys are derived. The application-specific key is handed out to the NAF client application in the terminal as response to the initial trigger made in step 2. The application-specific key is used to secure the communication with the application server.
5. The NAF client in the terminal sends transaction identifier to NAF server in the application server over Ua application interface. This transaction ID is needed, so that the NAF can contact the BSF and fetch the correct keys.
6. The NAF server in the application server contacts the BSF to obtain the application-specific session keys from BSF using transaction identifier over Zn key distribution interface.
7. The NAF server in the application server and the client in the terminal now share

Figure 2. HTTP based service request using GBA_ME (and GBA-unaware USIM)

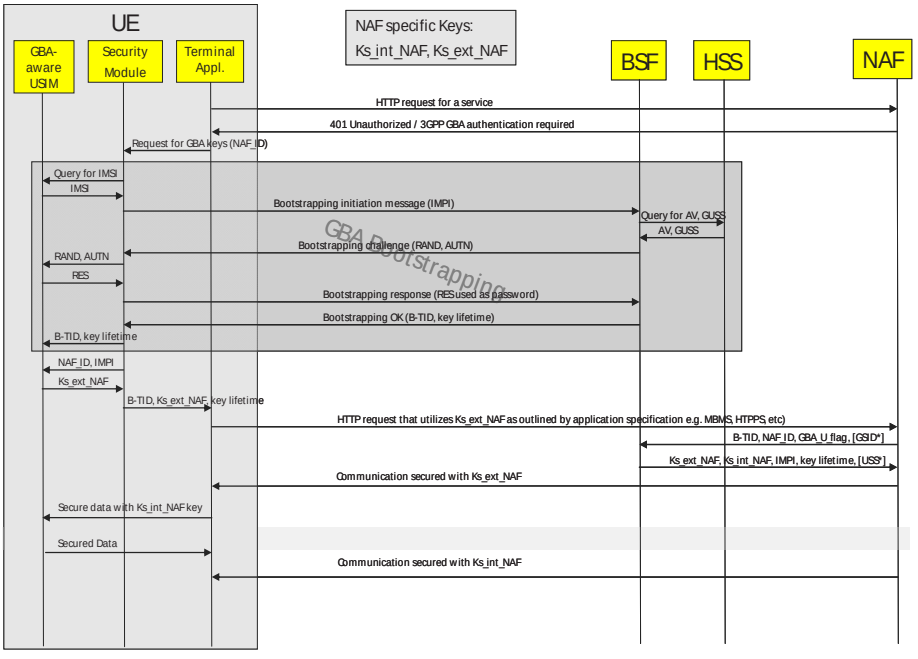


application-specific key(s) that they can use for authentication or other ways to secure the communication between terminal and application server.

In 3GPP there are basically three different ways to generate application-specific credentials in GBA. The previous basic steps are the same for all three types and should be seen as the basic GBA schemes. The variations were caused by different security requirements, business models, and market needs. The three GBA types are:

- **GBA_ME:** This is the terminal-based GBA. It requires a 3GPP UICC smart card, but the smart card does not need to be specially configured to support GBA_ME. The UICC can contain either an ISIM or a USIM application that can be used by GBA. The master session key and the application-specific keys are derived in the terminal. GBA_ME is also sometimes referred to as "normal GBA". Figure 2 outlines the message flow for GBA_ME. GBA_ME is defined in the 3GPP technical specification (3GPP TS 33.220, Release 6).
- **GBA_U:** GBA_U is a GBA type that requires a special smart card that supports GBA and is "GBA aware." The motivation for this was the cryptographic key generation is bound then very closely to the smart card and the issuing operator. The master key and the application-specific keys (Ks_ext_NAF and Ks_int_NAF) are derived in the GBA aware USIM application in an UICC. Only the Ks_ext_NAF application-specific session key is handed out to the terminal. A second application-specific session key Ks_int_NAF is not handed out and is stored and used only in the UICC. Figure 3 outlines the message flow for GBA_U. GBA_U is defined in (3GPP TS 33.220, Release 6). It should be noted, that the BSF modifies the AV received from the HSS. This gives an indication to the GBA-aware USIM, and the USIM returns just the RES and not the secret CK and IK keys to the terminal. The details on how those keys are used are defined by the application-specific documents, like MBMS (3GPP TS 33.246, 2006), HTTPS (3GPP TS 33.222, 2006) or

Figure 3. HTTP-based service request using GBA_U (GBA-aware USIM)



the OMA broadcast (BCAST) smart card profile.

- **2G GBA:** The 2G GBA or legacy GBA is a recent 3GPP GBA feature and defined in the technical report (3GPP TR 33.920, 2006) as an early implementation feature for Release 7. It outlines the usage of the SIM card for GBA. It should be noted, that it does not describe the usage of a legacy network nodes with GBA. The large deployment range of SIM cards created the need for a GBA credential generation solution that is based on legacy SIM cards and does not require immediate handing out of new UICC smart cards to the used. To obtain a similar security level than GBA_ME, the BSF node in the network is authenticated via a transport layer security (TLS) tunnel. The key derivation differs slightly, but the key usage is similar to GBA_ME. Figure 4 outlines the message flow for 2G GBA.

The notation for the Figures 2, 3, and 4 is that the * denotes an optional element.

In all, these three bootstrapping types have in common the basic steps outlined previously, and only the key generation and storage varies slightly. For the application server the usage of GBA_ME and 2G GBA is transparent. The convergence of fixed and mobile networks is, at the time of this writing, raising new GBA variants that will be discussed later in this chapter under Future Trends.

The specification family related to GBA has grown substantially due to new application requirements, further use cases, and new security enablers that were added. This will be outlined in the next section. The GBA can also be utilized to provision a user with a subscriber certificate and also trusted root certificate provisioning for public key infrastructure (PKI) systems. These are outlined in the 3GPP technical specification (3GGP TS 33.221, Release 6).

The term GBA refers typically to the core of GBA, where a master key is established between the mobile terminal (UE), and the network (BSF). Generic authentication architecture (GAA) on the other hand refers typically to the actual usage of the service specific keys that have been derived

Figure 4. HTTP based service request using 2G GBA

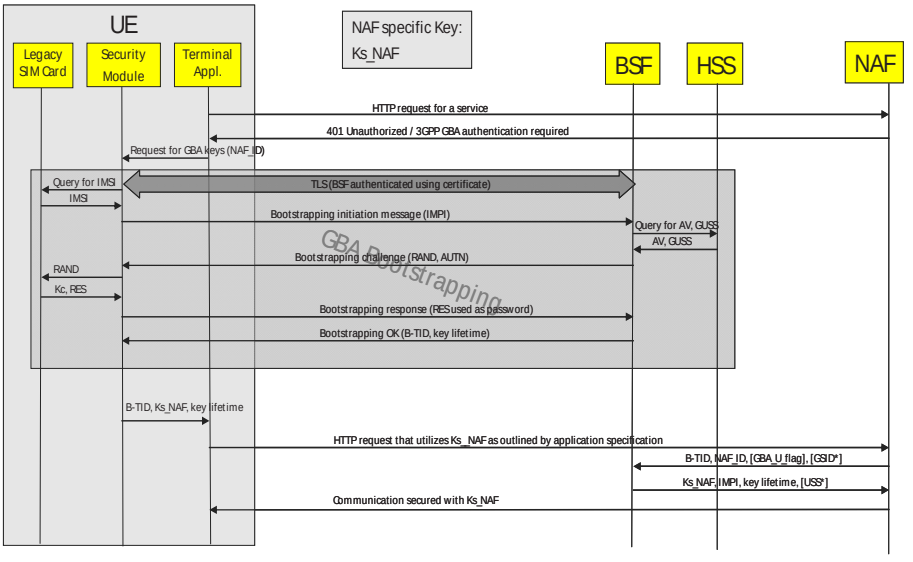
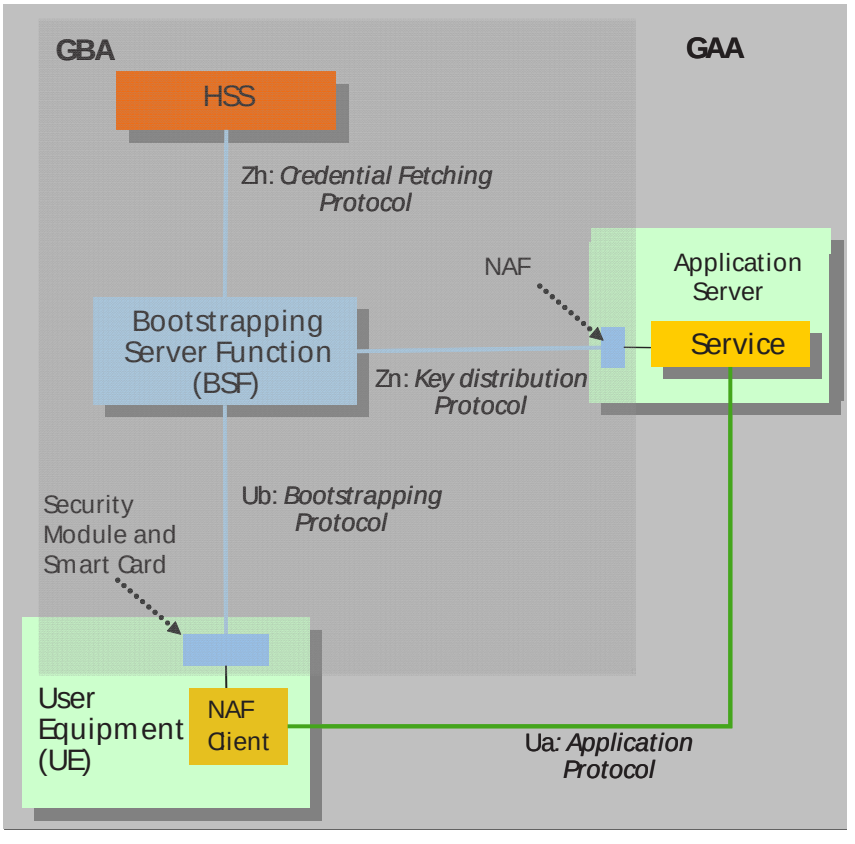


Figure 5. Generic authentication/bootstrapping architecture



from the master key. Thus, GBA refers to the core functionality and GAA to the actual usage of GBA in use cases, as depicted in Figure 5, but often it is not necessary to differentiate strictly.

GAA and GBA are not only evolving in 3GPP, but also in the American counterpart standardization organization the 3GPP2 (http://www.3gpp2.org/). 3GPP2 utilizes the removable user identity module (R-UIM) as a security baseline for their dialect of GBA. 3GPP2 GBA supports the 3GPP2 legacy algorithms Cellular Authentication and Voice Encryption (CAVE) algorithm, which is used in the American CDMA1x, standard and challenge handshake authentication protocol (CHAP), which is used in American code division multiple access (CDMA) 1xEvDo (evolution data only), but also AKA for the user authentication. For further details on 3GPP2 GBA, please consult the relevant specification (3GPP2 TS S.S0109-0, 2006).

APPLICATION SECURITY BASED ON THE GENERIC BOOTSTRAPPING ARCHITECTURE

In the beginning, GBA was developed to securely provide the user with subscriber certificates where the initial registration of the user to public key interface (PKI) system is authenticated using cellular authentication. The function to provide an application-specific shared secret based on the mobile credentials to a terminal and a network node evolved to a generic enabler for many use cases and service. In this context, terminal refers to 3GPP or 3GPP2 mobile phone.

GBA is not only used for a large range of applications that reside in a mobile network, but also for fixed broadband access security and their access devices (e.g. PC or laptop). The work on GBA for the next 3GPP Release 8 and the integration of GBA into future networks B3G will be discussed in the next section. In this section we outline the different existing applications that use GBA as a security enabler. We will not go into the details of each application, but focus on the usage of GBA.

Mobile Networks Applications Using GBA

GBA was initiated by 3GPP; hence the first applications that utilize GBA were also from 3GPP in their Release 6 and 7. The first service to mandate the usage of GBA is the 3GPP mobile broadcast/multicast service (MBMS) (3GPP TS 33.246, Release 6). The broadcast scenario poses some very special requirements on a key derivation and management system, that is, a content provider specific key that can be linked to a mobile user identity stored on the smart card, protection of the content protection keys (key confidentiality during transport), and the baseline security key should not be transported over the air. This resulted in the fact that MBMS has a quite sophisticated four layer key hierarchy, where the user-specific keys are established using GBA.

Another use case is general authenticated Web browsing. A user browses to a Web page that needs authentication. This is a quite common occurrence in the Internet and there a user typically then has to provide a username/password combination. Inserting a password on a mobile key pad is not very user friendly and would likely result in non-secure passwords, that is, without special characters, very short, no upper/lower case combinations. Many security solutions ignore the usability aspect and try to force the user, which usually results in more or less expensive password recovery systems. In the mobile environment, with a small key pad, inserting long, secure passwords with special characters is not user friendly. The integration of an automatic scheme that provides automatically an application-specific username/password pair to the browser request is therefore desirable for the mobile environment. From a user perspective, the authentication would either be seamless (i.e., the user does not even notice that this is ongoing) or it would be very similar to the user experience, where the password is stored by the browser. The technical side of the procedure runs as follows:

1. User contacts a service that requires HTTP digest authentication.

2. The service triggers the terminal to generate an application-specific shared secret. This is then established using GBA without further user interaction.
3. The transaction ID are put into the username field and the shared application-specific secret is put into the password field.
4. The data is validated and the user can access the service.

The details of this procedure can be found in the 3GPP specifications (3GPP TS 33.220, Release 6) and (3GPP TS 33.222, Release 6).

Web sites that request confidential data are often secured using TLS 1.0 or Secure Socket Layer (SSL) 3.0, which can be considered equivalent. GBA was integrated into the usage of TLS between a mobile terminal and an application server in 3GPP Release 6 (3GPP TS 33.222, Release 6). At the end of 2005 the Internet Engineering Task Force specified the usage of Pre-Shared Key TLS in the IETF (RFC 4279) (Eronen & Tschofenig, 2005). 3GPP integrated the PSK TLS, since pre-shared key computations are very suitable for low capability devices like mobile phones (3GPP TS 33.222, Release 6). It should also be noted, that PSK TLS can also be used with IETF Datagram TLS (Rescorla & Modadugu, 2006).

A user may access a service directly or through an authentication proxy (AP), that takes care of the authentication-related tasks on behalf of the actual application server. If an operator offers many services, then he/she may wish to deploy such an authentication proxy to centralize the user authentication task in one node. An AP is an HTTP reverse proxy which takes the role of the GBA NAF node (the application server) for the terminal. The AP handles the TLS security relation with the terminal and is the TLS end point. GBA is used to ensure for the application server that the service request is coming from an authorized user. The AP has the Zn interface towards the BSF and the Ua interface towards the terminal. When a HTTPS request is sent from the terminal to the application server that resides behind an AP, then the AP terminates the TLS tunnel and performs the terminal authentication. The AP proxies the HTTP requests received from UE to one or many application servers, depending on the request. The AP may add an assertion of identity of the subscriber for use by the application server, when the AP forwards the request from the terminal to the application server.

Operators can also utilize GBA for device management. For this use case, a device management server takes the role of a NAF and establishes a HTTPS tunnel to the UICC as outlined in the 3GPP technical report (3GPP TR 33.918, Release 7). Through this secure tunnel the device management information is then sent.

The European Telecommunications Standards Institute (ETSI) has a Smart Card Platform Group that has defined some use cases, like mobile banking and digital rights management (DRM), which require the existence of a secure channel between the terminal and the UICC smart card. They asked 3GPP to define the key management for this functionality. This was done based on GBA in the 3GPP technical specification (3GPP TS 33.110, Release 7) and is expected to be part of 3GPP Release 7. It remains to be seen which of the use cases defined by the smart card group will be implemented.

Network Agnostic Usage of GBA

GBA is also used outside of the classical mobile environment of 3GPP. The OMA defines bearer agnostic functionalities and services. Since authentication is in most cases bound to the bearer some specifications integrate the authentication of the underlying bearer and provide additional functionality for the case that another access type is used. GBA is used by the following OMA applications:

- **OMA broadcast smart card profile (BCAST)** (2007) defines the usage of a smart card profile for content protection using a four-layer key hierarchy based on GBA (similar to MBMS key hierarchy.
- In **OMA presence and availability working Group (PAG)** (2006) the content server relies on external authentication and authorization done for the presence sources that may reside

on the mobile terminal, and watcher nodes. For this authentication and authorization GBA as defined in 3GPP technical specification (3GPP TS 33.222, Release 6) can be used for that purpose, acting as an AP.

- **OMA secure user plane location (SUPL)** (2006) defines the usage of how the terminal can acquire the location of itself from the network, and this messaging between the terminal and the network can be optionally protected by GBA.
- **OMA XML document management (XDM) and OMA aggregation proxy** were specified by the OMA presence and availability working group (PAG) (2006). These specifications define mechanisms how terminals can manage XML documents in the network servers. The authentication can be optionally by based on GBA, and the authenticating node in the network can be either the XDM server itself, or it can be centralized using aggregation proxy, where all traffic to XDM servers is routed through the proxy.
- **OMA common security functions (CSF)** (OMA Security Working Group, 2005) defines a generic GBA Profile (GBAProfile) that acts as an enabler and that other OMA applications and enablers can use when they are defining the usage of GBA in them.

Another important standardization body, where GBA fits in is the Liberty Alliance Project. The Liberty Alliance Project enables identity federation (alias single sign-on) and Web service security. It is a non-mobile centric consortium that uses the provided user authentication, but does not specify the actual means of authentication and its context. This is left to the standardization bodies, which define the actual authentication method. 3GPP integrated their GBA to be used seamlessly with the Liberty Alliance Project Identity Federation Framework and the Web Service Framework. The details of this interworking are specified in 3GPP technical report (3GPP TR 33.980, Release 6).

These are only some examples of the possible usage of GBA outside of 3GPP, many non-standardized use cases are also enablers. GBA could be utilized for enterprise access or other use cases where a shared secret between a terminal and a network server is needed.

Fixed—Mobile Convergence and GBA

The term converging networks has become a key phrase in latest network evolution work. The trend to merge mobile and fixed network backend systems is caused by several factors:

- **Fewer and larger operators:** There is a general consolidation trend in the industry, which results in large, often international, operators. These operators often have a fixed network and a mobile network. For them it is important that they can use one backend to serve both access types.
- **New players:** The boundaries between technologies are vanishing, as voice over IP shows us. These new players appear and want to utilize the existing technology, but on the other hand want to preserve the investments into infrastructure. Especially, for fixed networks the investments are substantial. Multi-network devices are no longer future, but commercially available. This results in extensions to the existing "pure" mobile specific standards to integrate the new requirements and network types.
- **Seamless services:** The general mobility trend creates high user expectations, when something works with a fixed network, then it is also expected that is works seamlessly in a mobile environment. This can only be provided with a unified backend service system.

The fixed mobile convergence is focused around the IP multimedia subsystem (IMS), but GBA as a general security enabler for applications moved quickly into the scene. The most prominent drivers of mobile and fixed convergence outside of 3GPP are TISPAN and CableLabs.

The telecoms & Internet converged services & protocols for advanced networks (TISPAN) is a standardization body of the ETSI (n.d.). TISPAN focuses on fixed networks and migration from

switched circuit networks to packet-based networks with an architecture that can serve in both. TISPAN shares the same IMS specified by 3GPP. The idea is to keep the unity of IMS preserved by specifying the IMS core in 3GPP and TISPAN specific add-ons in TISPAN or 3GPP, depending on the working groups' agreements.

The TISPAN Release 1 which was finalized in 2006 is based upon the 3GPP IMS Release 6 and selected aspects of Release 7 architecture (which finishes early 2007). TISPAN standardizes functionalities or brings them into 3GPP for present and future converged networks, including the next generation networks (NGN). TISPAN utilizes GBA in their security architecture (ETSI TS 187.003, 2006) for the protection of the XML configuration access protocol (XCAP) traffic between a terminal and an application server using 3GPP TS 33.222 (2006) over their Ut interface. Optionally, an AP can be integrated into this interface.

CableLabs (http://www.cablelabs.com/) is a consortium of cable network providers with focus on Northern America. They are interested in utilizing the 3GPP specifications in their systems. In November 2006 a work item description that outlines the intended convergence security work was approved in 3GPP security group document number (3GPP Work Item Description S3-060764, 2006) with the title "IMS Enhancements for Security Requirements in Support of Cable Deployments." This work item proposes, among other extensions, also CableLabs specific extension to the 3GPP GBA "core" specification TS33.220 (Release 6). The outlined extensions include the possibility to bootstrap a shared secret from a username/password. In other words, the user would authenticate in a first step with his/her username/password. This pair would then serve as a baseline for further application-specific key generation. The user would not need to remember a new username/password pair for every service, but would potentially just have one CableLab username/password pair that could also be centrally managed. The details of this are work in progress and the final key derivation methods and further details still have to be fully defined in the near future (i.e., during year 2008).

FUTURE TRENDS AND GENERIC AUTHENTICATION IN BEYOND 3G NETWORKS

The wider deployment of adoption of GBA by the OMA created the need for a solution that an application server can trigger the key generation and send the needed key generation data (not the keys) to the mobile terminal. If this functionality is available it would allow that the continuous service provisioning and a broader usage of GBA-based functionalities for broadcast use cases. 3GPP started working on a Technical Specification GBA Credential Push Specification (3GPP TS 33.223, Release 8) that allows an application server (NAF) to trigger key generation procedure at the network side and push the required data to the terminal. Upon receiving this data the terminal would generate the keys without having a channel back to the network. The specification work for has started in 3GPP, and is targeted to be part of Release 8..

GBA has also been utilized to establish a shared secret between two entities. The main element in this use case is so-called NAF key center, and it can be used establish shared secret between either between the UICC and the ME (3GPP TS 33.110 Release 7) or between two devices where one of the devices is holding the UICC, and the other is not (3GPP TS 33.259, Release 7). This shared secret can then be used to secure the link between those two entities. The secure communication can then be used for any kind of application, for example, streaming.

The work on future networks after 3G has started in 3GPP. The work on the definition of a security framework for the core network system architecture evolution (SAE) and for the radio access network long term evolution (LTE) is ongoing. Sometimes, this work is also referred to as fourth generation (4G) or B3G networks. The work there assumes that there will be larger range of networks and that mobility between them is a key requirement. GBA was chosen as an enabler for mobile IP security in the setting that the related home agent (3GPP HA) resides in the 3G network. The SAE/LTE work is just evolving, so further usage of GBA and additions and modifications

can be expected with the progress of the work. On a high level, the basic trust relationship between the Mobile IP communication partners defines the needed security associations independently of the actual protocol version used.

There is the trust relationship between the terminal and the 3GPP authentication, authorization and accounting (AAA) server that resides in the user's home network and is in charge of the user authentication (e.g., using AKA) and authorization. This trust relationship is founded on the user's subscription to his/her home network and secured via a shared secret that can be assumed to be long-lived. The mobile IP authentication is independent of the access authentication, which is analogous to the case, where a user uses a service and requires authentication there. Hence, GBA could be could be used for mobile IP key provisioning.

The second trust relationship is between the 3GPP Mobile IP (MIP) HA and the user's terminal, so that the HA can act on behalf of the terminal for the tasks related to mobility. The relationship between these two entities is established dynamically (in the sense that there is no pre-provisioned shared secret) so the integrity of the MIP signaling can be ensured and depends on the actual mobile IP version used, that is, Mobile IP4 or Mobile IP6 (or DS-MIPv6). 3GPP has at the point of writing only made the decision for Mobile IP4. The decisions if MIPv6 or DS-MIPv6 will be used are not yet taken in 3GPP (status December 2006).

The third trust relationship is between the 3GPP MIP HA and the 3GPP AAA server. The trust between those nodes is high, since they are part of the same network for non-roaming case. For non-roaming cases there exist interoperator security protocols, like network domain security (NDS)/IP securityor IPsec. This trust relationship does not require GBA, since there is no user involvement.

CONCLUSION

The GBA allows secure provisioning of a shared secret to a mobile terminal and an application server based on cellular authentication. This shared secret can then be used for many purposes, like username/password authentication, certificate enrollment, DRM, and so forth. GBA was originally designed by the 3GPP, but has recently been taken up for long term evolution networks, fixed broadband access, and cable networks.

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KEY TERMS

Application Security: Application security encompasses a large range of measures taken to prevent incidents with respect to the security policy of an application or the underlying framework. Application security is realized through design and deployment of the application.

Authentication And Key Agreement (AKA): AKA is a mechanism where a mobile device and mobile network operator authenticate and distribute shared key(s) to be used between them. This process is based on a long-term shared secret that is in the mobile terminal (namely in UICC, e.g., SIM card), and mobile network operators databases (e.g., Home Location Register [HLR]). GBA is based on this process.

Authentication: Authentication is the attempt to verify the digital identity of the sender of an authentication request.

Cellular Authentication: Cellular authentication is the authentication process that is used when a mobile phone is attached to a network (e.g., GSM or UMTS network). This authentication is based on a smart card that is inserted in the mobile phone.

Generic Authentication Architecture (GAA): GAA is an architecture that is built on top of GBA that utilizes the shared secret to gain access to service.

Generic Bootstrapping Architecture (GBA): GBA is an architecture where cellular authentication is used to bootstrap a shared secret between a mobile phone and a network node.

Mobile Application: Mobile application is an application that resides on a server and can be accessed or consumed by a mobile device. The application may require a dedicated software element in the mobile terminal (e.g., for mobile TV).

Second Generation Generic Bootstrapping Architecture (2G GBA): 2G GBA describes the usage of the GBA with legacy SIM smart cards. It does not contain the integration of legacy network nodes.

Universal Integraged Circuit Card (UICC): UICC is the smart card (e.g., SIM card) used in mobile terminals in GSM and UMTS networks.

Chapter XXV
Authentication, Authorization, and Accounting (AAA) Framework in Network Mobility (NEMO) Environments

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ABSTRACT

Network mobility (NEMO) enables seamless and ubiquitous Internet access while on-board vehicles. Even though the Internet Engineering Task Force (IETF) has standardized the NEMO basic support protocol as a network layer mobility solution, little studies have been conducted in the area of authentication, authorization, and accounting (AAA) framework that is a key technology for successful deployment. In this article, we first review the existing AAA protocols and analyze their suitability in NEMO environments. After that, we propose a localized AAA framework to retain the mobility transparency as the NEMO basic support protocol and to reduce the signaling cost incurred in the AAA procedures. The proposed AAA framework supports mutual authentication and prevents various threats such as replay attack, man-in-the-middle attack, and key exposure. Performance analysis on the AAA signaling cost is carried out. Numerical results demonstrate that the proposed AAA framework is efficient under different NEMO environments.

INTRODUCTION

With the advances of wireless access technologies (e.g., third generation [3G], IEEE 802.11/16/20) and mobile communication services, the demand for Internet access in mobile vehicles such as trains, buses, and ships is constantly increasing (Ott & Kutscher, 2004). In these vehicles, there are multiple devices constituting a vehicular area network (VAN) or personal area network (PAN) that may access to Internet. This kind of services is referred to network mobility (NEMO) services. Recently, many studies have been conducted for network mobility (Information Society Technologies [IST], 2003; Keio University, 2002). Regarding mobility management, the Internet Engineering Task Force (IETF) has established a working group called NEMO (IETF, 2006) and the NEMO working group has proposed an extended Mobile IPv6 protocol (Johnson, Perkins, & Arkko, 2003), that is, the NEMO basic support protocol (Devarapalli, Wakikawa, Petrescu, & Thubert, 2005). Throughout this chapter, we consider the NEMO basic support protocol as a mobility management framework.

According to the terminologies in Ernst and Lach, 2005), a mobile network (MONET) is defined as a network whose point of attachment to the Internet varies as it moves about. A MONET consists of mobile routers (MRs) and mobile network nodes (MNNs). Each MONET has a home network to which its home address belongs. When the MONET is in the home network, the MONET is identified by its home address (HoA). On the other hand, the MONET configures a care-of-address (CoA) on the egress link when the MONET is away from the home network. At the same time, on the ingress link, the MNNs of the MONET configure CoAs, which are derived from the subnet prefix (i.e., mobile network prefix [MNP]). The MNP remains assigned to the MONET while it is away from the home network. The assigned MNP is registered with the home agent (HA) according to the NEMO basic support protocol.

The main objective of the NEMO basic support protocol is to preserve established communications between the MONET and correspondent nodes (CNs) during movements. Packets sent by CNs are first addressed to the home network of the MONET. Then, the HA intercepts the packets and tunnels them to the MR's registered address, that is, the CoA on the egress link. To deliver packets towards the MR's CoA, the NEMO basic support protocol makes a bi-directional tunnel between the HA and the MR. This tunneling mechanism is similar to the solution proposed for host mobility support, that is, Mobile IPv6 without route optimization.

To make network mobility services feasible in public wireless Internet, well-defined authentication, authorization, and accounting (AAA) protocols should be accompanied. However, to the best of our knowledge, little work has been conducted for AAA protocols in network mobility services. Even though a number of AAA protocols have been proposed for host mobility, all of them are based on per-node AAA operations and therefore they cannot be directly applied to the MONET containing two different types MNNs: local fixed nodes (LFNs) and visiting mobile nodes (VMNs). An LFN belongs to the subnet to the MR and is unable to change its point of attachment, while a VMN is temporarily attached to the MR's subnet by obtaining its CoA from the MNP. The VMN's home network may have different administrative policy (e.g., billing) from the current attached MONET. Therefore, a new AAA procedure for VMNs is required.

In this chapter, we propose a localized AAA protocol that provides efficient AAA procedures for both LFNs and VMNs in NEMO environments. The proposed AAA protocol is consistent with the NEMO basic support protocol. In other words, individual AAA operations for LFNs within a MONET are not performed; instead, the MR is authenticated on behalf of the LFNs. On the other hand, each VMN attached to the MONET performs its AAA operation in an individual manner. The proposed AAA protocol has the following advantages: (1) the proposed AAA protocol localizes the AAA procedure using a local AAA key when the MR hands off within the same foreign network. Therefore, the AAA signaling traffic (also, the AAA latency) can be significantly reduced. We analyze the AAA signaling traffic via an analytical model in the

Signaling Cost Analysis section; (2) the proposed AAA protocol allows mutual authentication and prevents various security attacks such as replay attack and man-in-the-middle attack. The security analysis is given in the fourth section; (3) from the point of view of Internet service providers (ISPs), how to charge a VMN for its network usage is a critical issue. The proposed AAA protocol supports a flexible billing mechanism in which the VMN is informed of a billing agreement between the MR's home network and the new foreign network. Accordingly, the proposed AAA protocol is a suitable solution when the MONET hands off between different networks with different billing or service policies.

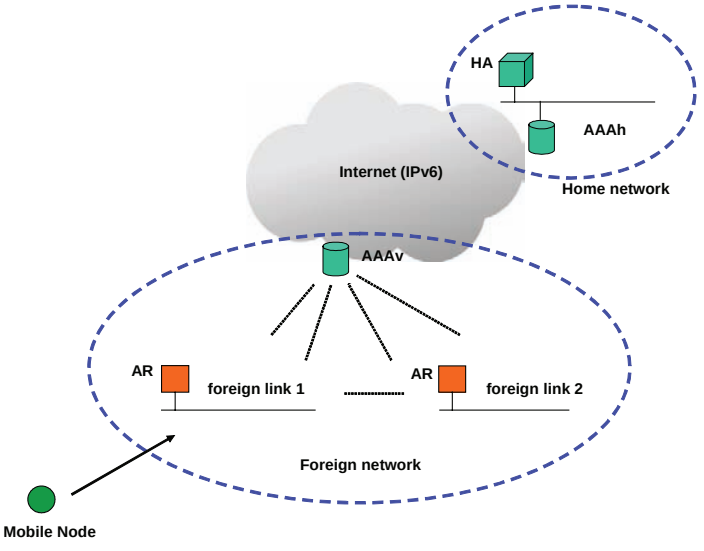
The remainder of this chapter is organized as follows. In the next section, an existing AAA protocol for Mobile IPv6 is introduced as a reference protocol. The third section proposes a localized AAA protocol and the fourth section analyzes the security of the proposed AAA protocol. In the fifth section, an analytical model for the AAA signaling cost is developed and numerical results are presented, respectively. The sixth section concludes this chapter.

BACKGROUND

In this section, the AAA protocol in Mobile IPv6 is described as a reference model. Although several AAA protocols have been proposed in the literature, we adopt the Diameter extension for Mobile IPv6 protocol (Le, Patil, Perkins, & Faccin, 2004) because it is the only valid IETF Internet draft as of this writing. The Diameter extension for Mobile IPv6 allows a mobile node (MN) to access a network of a service provider after the AAA procedures based on the Diameter protocol (Calhoun, Loughney, Guttman, Zorn, & Arkko, 2003) is completed.

This protocol considers a network architecture for AAA services, as shown in Figure 1. The AAAv is an AAA server in the visited (foreign) network, while the AAAh is an AAA server in the home network of the MN. Hereafter, we assume that the AAA client is located at each access router (AR). The AAA client performs three tasks: (1) allowing the MN to be authenticated, (2) generating accounting data for the MN's network usage, and (3) authorizing the MN to use network resources. By Le et al. (2004) an MN is identified by its network access identifier (NAI) (Aboda & Beadles,

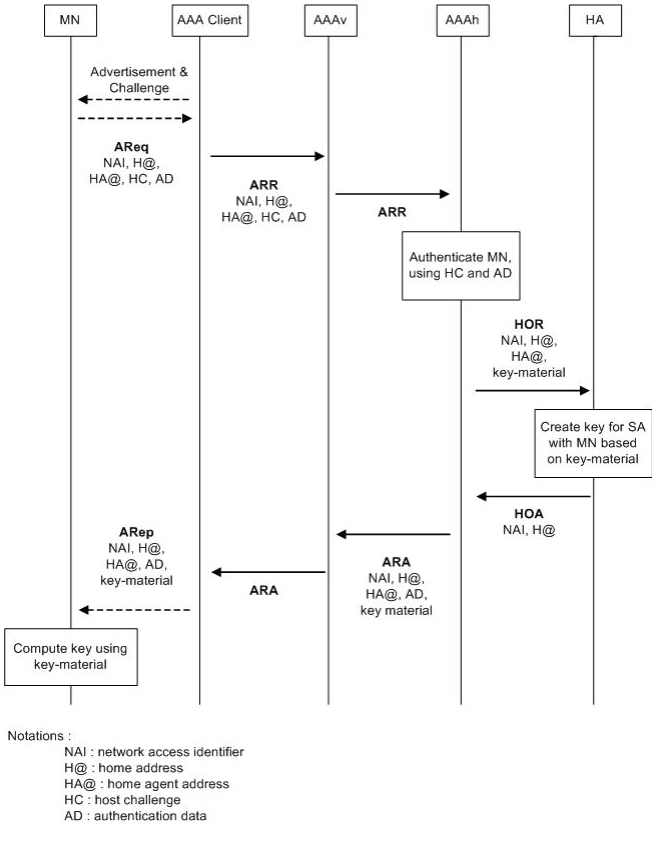
Figure 1. Mobile IPv6 AAA architecture



1999), which is globally unique. An MN and its AAAh have a long-term key, and communication between the AAAv and AAAh is secure.

The message flow in the Diameter extension for Mobile IPv6 is illustrated in Figure 2. When entering a new network or at power up, an MN listens to an AR's router advertisement (RA) message which has a local challenge and a visited network identifier. Then, the MN sends an authentication request (AReq) message to the AAA client (i.e., AR) based on the security key shared with its AAAh. When the AAA client receives the AReq message, it creates an AA-Registration-Request Command (ARR) message and sends it to the AAAv. Then, the AAAv relays it to the AAAh of the MN. When receiving the ARR message from the AAAv, the AAAh authenticates the MN by means of the NAI and sends a Home-Agent-MIPv6-Request Command (HOR) message to the MN's HA. Upon receipt of the HOR message, the HA creates a key to establish a security association (SA) with the MN, and replies with a Home-Agent-MIPv6-Answer Command (HOA) message to the AAAh. Then, the AAAh constructs the AA-Registration-Answer Command (ARA) message that has an authentication result and sends it to the AAAv. When receiving the ARA message from the AAAh, the AAAv stores the authentication result locally and then forwards the message to the AAA client. The AAA client converts the ARA message into the authentication reply (ARep) message, in order to inform the MN of the authentication result from the AAAh and deliver the established key (for the SA) to the MN.

Figure 2. Message flow in the AAA protocol for Mobile IPv6



LOCALIZED AAA FRAMEWORK IN NEMO ENVIRONMENTS

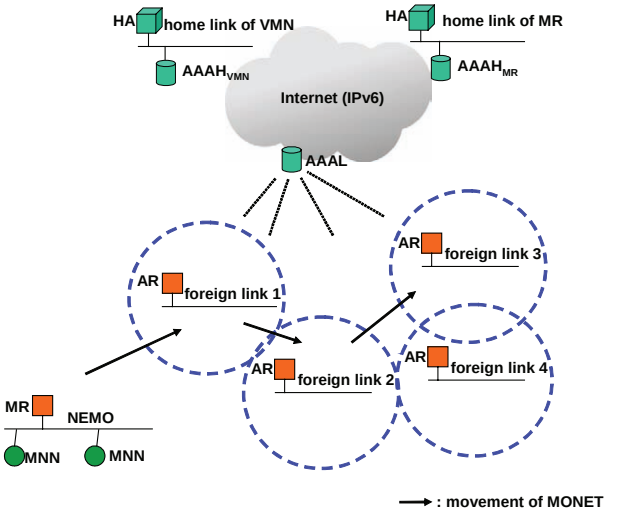
System Architecture

In this section, the AAA architecture in NEMO environments is introduced with basic assumptions and concepts (e.g., SA and challenge/response authentication). Figure 3 illustrates the reference AAA architecture in NEMO environments based on the Diameter protocol.

The AAA architecture consists of multiple autonomous wireless networks, each of which is called a domain. Each domain has an AAAH server and/or an AAAL server in order to authenticate any node in a Diameter-compliant manner. The AAAH server of the MR has the profile of the MR and it shares a long-term key with the MR. Likewise, the AAAH server of the VMN shares a long-term key with the VMN. The AAAL server is in charge of an AAA procedure for a visiting MONET (i.e., VMNs and MRs). The trust relationship between the MR's AAAH server and the AAAL server in the visited network is maintained through the Diameter protocol.

When the MONET changes its point of attachment, the MR needs to be authenticated and authorized before it accesses a new domain in the same foreign network (i.e., intra-domain handoff) or a new foreign network (i.e., inter-domain handoff). To accomplish this, the MR and AR authenticate each other through a mutual authentication procedure that involves both the AAAH server of the MR and the AAAL server of the AR. An attendant (which is the same as an AAA client) is an entity that triggers authentication procedures to the AAA system. In Mobile IPv6 networks, ARs normally act as the attendants for an MN. In the proposed AAA protocol, the AR serves as an attendant for the MR's authentication, whereas the MR serves as an attendant for VMN's authentication. In the latter case, the MR broadcasts attendant advertisement messages and receives authentication request messages from VMNs within a MONET. In other words, an attendant (an AR or MR) requests the AAAL server to authenticate the MONET (the MR or VMN). When the AAAL server receives the authentication request, it verifies the identity of the MONET by cooperating with an AAAH server. In terms of SAs, we assume that the MR's AAAH server and the VMN's AAAH server have

Figure 3. AAA architecture in NEMO environments



a pre-established SA. In addition, it is assumed that the MR and LFNs have already authenticated each other by a mechanism, which is beyond scope of this chapter.

Notations used in this chapter are summarized in Table 1. A local challenge (LC) is a random number for authentication procedures. An MR or VMN encrypts the LC using a pre-defined SA with its AAAH server. The encrypted value is called a credential (CR), which is used to authenticate an MR that creates it. MRs and VMNs are identified by their NAIs and a replay protection indicator (RPI), which is used to protect from a replay attack. Either a timestamp or a random number can be used as an RPI. The size of the K_{AAA} field is 128 bytes by assuming a public key cryptography algorithm. We adopt a symmetric key cryptography for dynamic keys K_{LOCAL} and K_{HOME}, and their sizes are 32 bytes. Note that a dynamic key is used to establish a dynamic SA while a long-term key is to establish a long-term SA. Other notations will be elaborated later.

In the proposed AAA protocol, we define two Internet Control Message Protocol (ICMP) messages (Conta & Deering, 1998), Attendant Solicit and Attendant Advertisement messages, which are similar to Router Solicit and Router Advertisement messages, respectively. In these messages, we introduce a new Attendant advertisement option and it is used for the authentication of VMNs for an intra-domain handoff. In addition, several Diameter messages, for examples, AA-Mobile-Router-Request and AA-Mobile-Router-Answer, are defined. Their functions will be described later.

Table 1. Notations for the localized AAA protocol

Field	Meaning	Typical Length (bytes)
LC	local challenge	8
MC	mobile challenge	8
NAI	identity of MR or VMN	20
RPI	replay protection indicator	4
H@	home address	16
HA@	home agent address	16
Co@	care of address of MR or VMN	16
K_{AAA}	pre-shared SA between an MR and an AAAH server	128 (public key)
K_{AH}	pre-shared SA between an AAAH server and an HA	128 (public key)
K_{AL}	pre-shared SA between an AAAH server and an AAAL server	128 (public key)
CR	credential	8
CR_L	local credential	8
K_{LOCAL}	dynamic SA between an MR and an AAAL server	32 (symmetric key)
CR_M	mobile credential	8
K_{HOME}	dynamic SA between an MR and its AAAH server	32 (symmetric key)
SP_{LOCAL}	security parameters for constructing K_{LOCAL}	12
SP_{HOME}	security parameters for constructing K_{HOME}	12

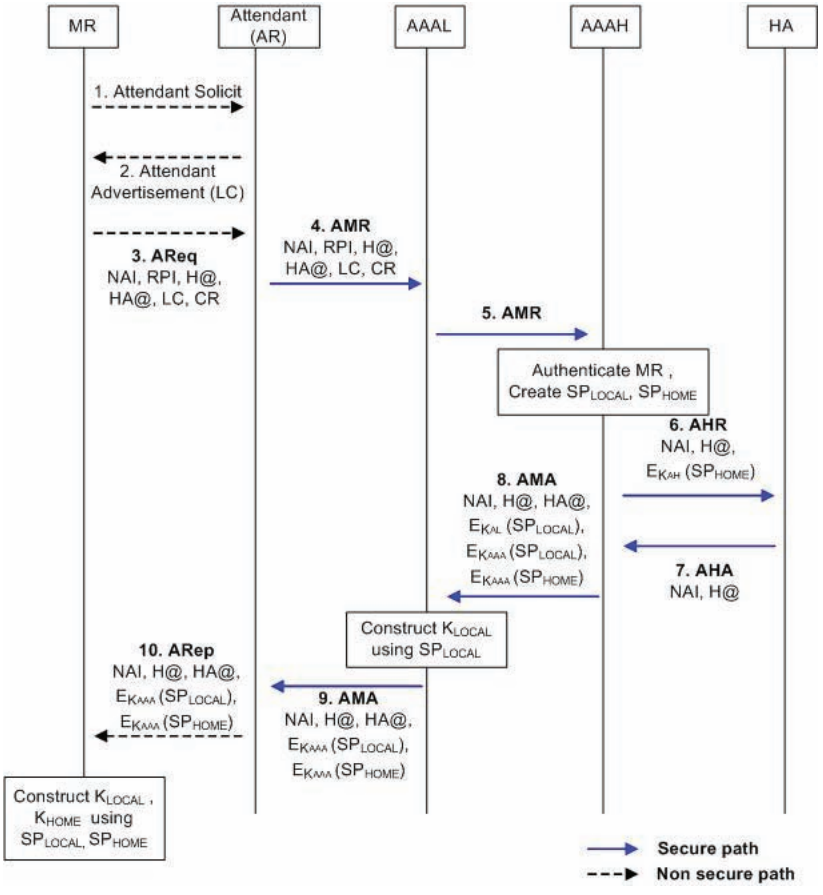
Mobile Router Authentication

Inter-Domain AAA Procedure

When a MONET enters a new foreign network domain, an inter-domain AAA procedure is triggered. Since the MR does not have any SA with the AAAL server in the foreign network domain, it should be authenticated with its AAAH server located in its home network domain. The message flows for the inter-domain AAA procedure are illustrated in Figure 4 and the detailed descriptions are as follows:

- **Step 1:** The MR sends an Attendant Solicit message to the attendant, that is, AR.
- **Step 2**: As a response to the Attendant Solicit message, the AR sends an Attendant Advertisement message including an LC. Even without the Attendant Solicit message, the AR broadcasts Attendant Advertisement messages periodically.
- **Step 3:** The MR encrypts the received LC value using its long-term SA with the AAAH server and makes a CR, which enables the MR's AAAH server to authenticate the MR. Then, the MR sends an AReq message that contains the LC and CR to the AR (i.e., attendant). The AReq message also contains the MR's NAI and RPI, which are used for the AAAL server to identify the MR's home domain and to protect from replay attack.
- **Step 4:** When the AR receives the AReq message, it converts it into an AA-Mobile-Router-Request (AMR) message. After then, the AR sends the AMR message to the AAAL server in the foreign domain.
- **Step 5:** The AAAL server detects that it cannot authenticate the MR locally by checking the NAI field and hence forwards the AMR message to the MR's AAAH server. When the AAAH server receives the AMR message, it encrypts the LC using the pre-established SA and compares the result with the CR value. If these two values are identical, the MR is successfully authenticated. Then, the AAAH server generates two dynamic keys: one is a K_{LOCAL} (to be explained later) for intra-domain AAA procedures in the foreign domain and the other is a K_{HOME} for a secure bi-directional tunnel between the MR and the MR's HA. To allow the MR to generate K_{LOCAL} and K_{HOME}, the AAAH server also generates SP_{HOME} and SP_{LOCAL}, and sends them to the MR. These security parameters are encrypted using the long-term key between the MR and AAAH server to avoid the possibility of exposure to other network entities.
- **Step 6:** The AAAH server informs the HA of the MR's NAI and SP_{HOME} using the AA-Home-Agent-Request (AHR) message.
- **Step 7:** The HA constructs K_{HOME} by using SP_{HOME} and replies with an AA-Home-Agent-Answer (AHA) message as confirmation.
- **Step 8:** The AA-Mobile-Router-Answer (AMA) message is used for the AAAH server to notify the AAAL server of the authentication result. When the AAAL server receives the AMA message with authentication approval, the AAAL server decrypts the message using the long-term key (K_{AL}) with the AAAH server, records the MR's NAI, and constructs K_{LOCAL}.
- **Step 9:** The AAAL server re-encrypts the received AMA message from the AAAH server after excluding $E_{KAL}(SP_{LOCAL})$ and sends it to the AR.
- **Step 10:** When receiving the AMA message, the AR learns that the MR is successfully authenticated and grants the MR's network access. Therefore, the AR informs the MR of the result by the ARep message containing SP_{HOME}, SP_{LOCAL}, home agent address, and so forth. On receipt of the ARep message with authentication approval, the MR can access the foreign network. At the same time, the MR generates K_{HOME} and K_{LOCAL} using SP_{HOME} and SP_{LOCAL}, respectively.

Figure 4. MR's AAA procedure for inter-domain handoff

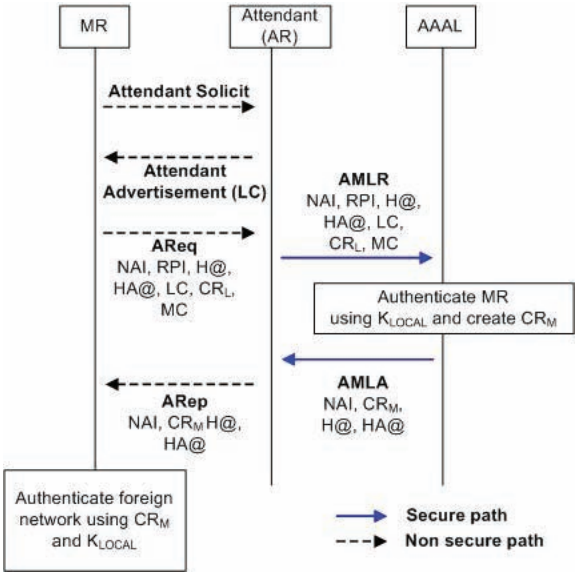


Intra-Domain AAA Procedure

To support real-time multimedia applications in NEMO environments, it is important to reduce the latency for AAA operations. Therefore, when a MONET changes its point of attachment within the same foreign domain, our protocol enables the MR to be authenticated through a localized AAA procedure with the AAAL server in the foreign network without any interaction with its AAAH server. That is, the AAAL server of the foreign network can authenticate the MR using K_{LOCAL}, which was introduced for the inter-domain AAA procedure in the previous section.

Figure 5 illustrates the intra-domain AAA procedure. As a response to the Attendant Advertisement message, the MR sends the AReq message containing CR_L, which is different from CR used in the inter-domain AAA procedure. At this time, the AReq message contains MC for mutual authentication. The CR_L is an authentication code generated using K_{LOCAL}. Then, the attendant constructs an AA-Mobile-Router-Local-Request (AMLR) Diameter message and sends it to the AAAL server. When the AAAL server receives the AMLR message, the AAAL server authenticates the MR by using K_{LOCAL}, which has been already stored at the AAAL server during the inter-domain AAA procedures. Moreover, the AAAL server constructs CR_M by encrypting the MC value and informs the AR of the result via the AA-Mobile-Router-Local-Answer (AMLA) message. Then, the AR transmits the result (i.e., the ARep message) to the MR. The MR receiving the ARep message verifies the CR_M value to authenticate the foreign network, that is, mutual authentication.

Figure 5. MR's AAA procedure for infra-domain handoff



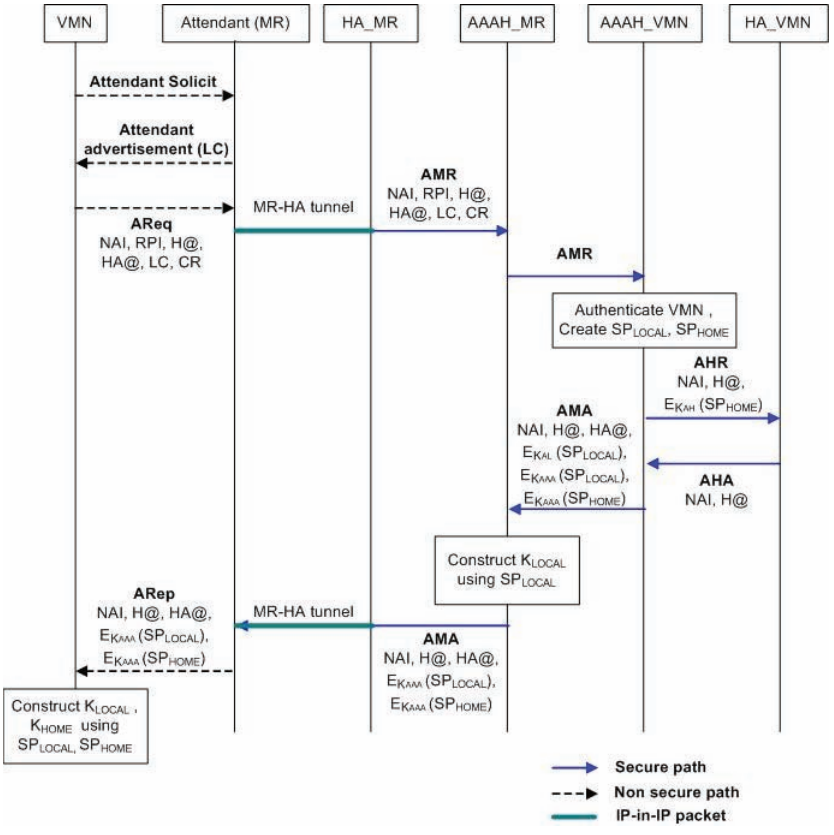
Visiting Mobile Node (VMN) Authentication

A VMN is a visiting MN that accesses the Internet through an MR in a MONET. According to the NEMO basic support protocol, the VMN does not need to know whether its attached router is the AR or the MR. Therefore, the AAA protocol for VMNs should be consistent with this requirement. The VMN in a MONET uses the home network prefix of the MR as its IPv6 network prefix. Accordingly, the VMN will deem it to be in the MR's home network. For VMN authentication, the MR serves as an attendant for VMNs and the MR's AAAH server serves as an AAAL server.

Figure 6 illustrates message flows for the AAA procedure when a VMN is attached to a MONET. As mentioned previously, the MR acts as an attendant. Hence, the MR broadcasts Attendant Advertisement messages periodically or responds to an Attendant Solicit message from the VMN with an Attendant Advertisement message. The VMN creates a CR using a pre-shared SA with its AAAH server ($AAAH_{VMN}$) and sends an AReq message to the MR. Then, the MR converts the AReq message into a Diameter message, AMR, and then sends it to the MR's AAAH server ($AAAH_{MR}$) through a secured bi-directional tunnel. When the $AAAH_{MR}$ receives the AMR message, it sends the AMR message to the $AAAH_{VMN}$ that has a shared SA and requests the AAA procedure for the VMN. Then, the $AAAH_{VMN}$ authenticates the VMN. During these steps, K_{HOME}, K_{LOCAL}, SP_{HOME}, and SP_{LOCAL} are created, which is similar to the inter-domain AAA procedure of the MR. After completion of AAA procedures, the VMN registers its CoA (configured using the MNP) with its HA.

After the initial authentication and binding update procedures, VMNs within a MONET do not need to know whether the MONET changes its point of attachment or not. Thus, VMNs do not have to register their locations to their HAs even though the MONET hands off. This mobility transparency is the key advantage of the NEMO basic support protocol. However, if the mobility transparency is strictly provided, the AAAL server in the foreign network cannot detect the existence of VMNs. In other words, the mobility transparency is beneficial to reduce the binding update traffic, however, it makes the accounting/billing of VMNs' network usages hard. To address this problem, in our protocol, the AAAL server in the

Figure 6. VMN's AAA procedure



foreign domain accounts the total network usage of the MONET (not individual VMNs) and then this collective accounting/billing information is delivered to the MR's AAAH server. At the same time, the MR's AAAH server maintains the accounting/billing information for the MR as well as individual VMNs.[1] Consequently, the MR's AAAH server can differentiate the accounting/billing information for MRs and VMNs. In addition, we assume that the MR's AAAH server and the VMN's AAAH server have a trust relationship and a shared SA. Therefore, the accounting/billing information collected at the MR's AAAH server is securely transferred to the VMN's AAAH server for suitable billing.

In addition, the mobility transparency causes another problem, that is, how to authorize VMNs when the MONET moves to a foreign domain with a different billing policy. To solve this problem, an MR sends an Attendant Advertisement message with a set R bit when the foreign domain has a different policy and thus a new AAA procedure is required. Hence, from the Attendant Advertisement message, the VMN determines whether it should perform a new AAA procedure or not. We assume that each network domain can have different policies, so that the VMN performs a new AAA procedure for each inter-domain handoff.

SECURITY ANALYSIS

In this section, we analyze the proposed AAA protocol in terms of mutual authentication and security attacks (e.g., key exposure, replay attack, and man-in-the-middle attack).

Mutual Authentication

Mutual authentication is a security feature in which a client (i.e., the MR and VMN) must prove its identity to a service (i.e., network), and the service must prove its identity to the client. To provide mutual authentication in the NEMO AAA protocol, two requirements should be satisfied: (1) the MR or VMN authenticates the foreign network; and (2) the foreign network authenticates the MR or VMN.

Specifically, mutual authentication in the proposed AAA protocol is achieved as follows. First, for the inter-domain authentication, mutual authentication is provided by establishing a session key, K_{LOCAL}. In other words, the objective of inter-domain authentication protocol is that the MR and the AAAL server believe that they share K_{LOCAL} with each other. The MR creates CR as

$$CR = E_{K_{AAA}}(LC) \quad (1)$$

where $E_K(\cdot)$ is an encryption function using a key of K. The AAAH server can verify the MR's identity by comparing with CR sent by the MR with the CR constructed by the AAAH server itself. If two values are identical, the MR is successfully authenticated. Otherwise, the authentication fails. In our protocol, a malicious MR cannot create the correct CR because it does not have K_{AAA}. After verifying the identity of the MR, the AAAH server transmits $E_{K_{AAA}}(SP_{LOCAL})$ and $E_{K_{AL}}(SP_{LOCAL})$ to the AAAL server through a secure path. When the AAAL server receives, it constructs K_{LOCAL} using $E_{K_{AL}}(SP_{LOCAL})$ and forwards $E_{K_{AAA}}(SP_{LOCAL})$ to the MR. At last, the MR constructs K_{LOCAL} using $E_{K_{AAA}}(SP_{LOCAL})$. After this procedure, the MR and the AAAL server share K_{LOCAL}.

For the intra-domain authentication, the AAAL server in the foreign network verifies the identity of the MR by comparing $E_{K_{LOCAL}}(LC)$ constructed by the AAAL server with CR_L sent by the MR. On the other hand, to authenticate the foreign network, the MR uses an MC and CR_M. The AAAL server in the foreign network sends CR_M that is created by

$$CR_M = E_{K_{LOCAL}}(MC) \quad (2)$$

Then, the MR can authenticate the AAAL server in the foreign network by verifying that $E_{K_{LOCAL}}(MC)$ is equal to CR_M. Consequently, a malicious network cannot offer fake services to an MR because it cannot compute CR_M, and mutual authentication is achieved.

Key Exposure

K_{AAA} is a pre-shared key between an MR and the AAAH server, and K_{LOCAL} and K_{HOME} are created using security parameters, SP_{LOCAL} and SP_{HOME}, respectively. Thus, it is desirable not to leak these keys to the other network entities.

With respect to K_{LOCAL}, the AAAH server encrypts SP_{LOCAL} using K_{AL} and sends it the AAAL server. At the same time, the AAAH server send the encrypted SP_{LOCAL} using K_{AAA} to the MR. Therefore, the encrypted SP_{LOCAL} can be decrypted only by the AAAL server and the MR because they have K_{AL} or K_{AAA}. In other words, if K_{AL} and K_{AAA} are not exposed, any other entities except the AAAL server and the MR cannot know SP_{LOCAL} and thus cannot construct K_{LOCAL}. Similarly, SP_{HOME} is encrypted using K_{AH} and K_{AAA}, and delivered to the HA and MR, respectively. Therefore, K_{HOME} derived from SP_{HOME} is not revealed to other entities except the HA and MR.

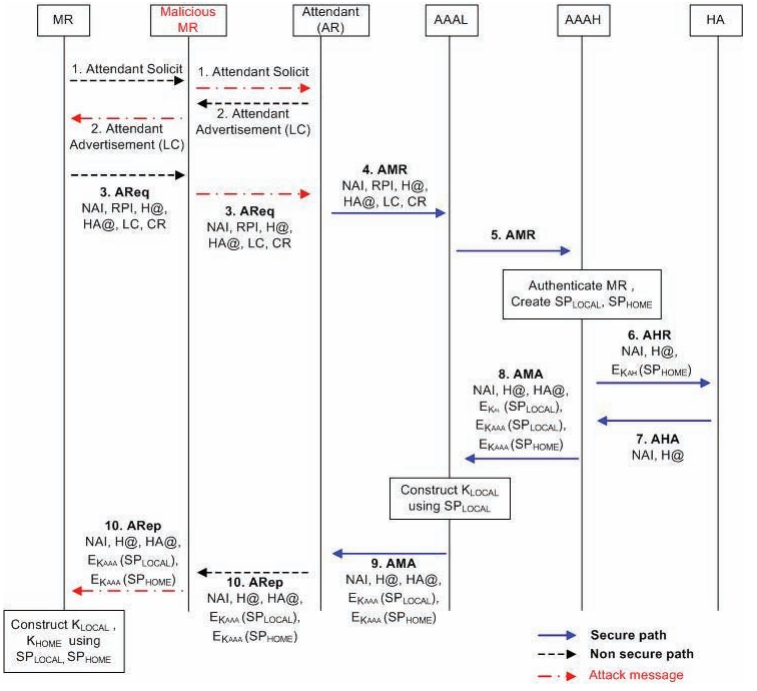
Replay Attack

Replay attack involves the passive capture of data and its subsequent retransmission to produce an unauthorized effect. A malicious node keeps an AReq message and then it can retransmit an old AReq message to trick the AAAL server for false authentication. In our protocol, LC is created randomly and hence it always changes and therefore the malicious node cannot replay the old AReq message. Even though the same LC is selected by the attendant, RPI (i.e., timestamp) can prevent the replaying attack.

Man-in-the-Middle Attack

A man-in-the-middle attack represents that an attacker is able to read, insert, and modify messages

Figure 7. Man-in–the-middle attack by a malicious MR



between two parties without either party knowing that the link between them has been compromised. In NEMO environments, we can imagine an attack that a malicious MR relays authentication messages and it intends to use network resource illegally. Figure 7 illustrates the man-in–the-middle attack by a malicious MR for the inter-domain authentication. The malicious MR acts as an AR and relays authentication messages between the victim MR and the AR. After the authentication procedures, the malicious MR still can relay all of the traffic between the victim MR and AR. However, the malicious MR cannot use any network resource because it has no knowledge of K_{LOCAL} and K_{HOME}. Namely, if a fresh session key is established, the malicious MR cannot further compromise the authentication procedure between the MR and the AAAL server.

SIGNALING COST ANALYSIS

Reducing the AAA traffic is an important requirement in NEMO environments where a MONET moves with a high velocity and AAA procedures are frequently performed (e.g., train or car). Therefore, through the analytical model, we quantify the AAA cost (C_{AAA}), which is defined as the volume of AAA-related messages delivered over the network and the unit of C_{AAA} is bytes * hops (Lo, Lee, Chen, & Liu, 2004).

Let i and j be the numbers of intra-domain handoffs and inter-domain handoffs for each session, respectively. It is assumed that the subnet residence time of the MONET follows a general distribution with mean $1/\mu_S$, which probability density function (PDF) is $f_S(t)$ and its Laplace transform is $f^*_S(s)$. In addition, the domain residence time of the MONET follows a general distribution with mean $1/\mu_D$, whose PDF is $f_D(t)$ and its Laplace transform is $f^*_D(s)$. When the inter-session arrival time is assumed to be an exponential distribution with rate λ_I, the PDFs of i and j are respectively given by (Lin, 1997)

$$\alpha(i) = \begin{cases} 1 - \frac{1}{\rho_S}[1 - f_S^*(\lambda_I)] & i = 0 \\ \frac{1}{\rho_S}[1 - f_S^*(\lambda_I)]^2 [f_S^*(\lambda_I)]^{i-1} & i > 0 \end{cases}$$

and

$$\beta(j) = \begin{cases} 1 - \frac{1}{\rho_D}[1 - f_D^*(\lambda_I)] & j = 0 \\ \frac{1}{\rho_D}[1 - f_D^*(\lambda_I)]^2 [f_D^*(\lambda_I)]^{j-1} & j > 0 \end{cases}$$

where $\rho_S = \lambda_I / \mu_S$ and $\rho_D = \lambda_I / \mu_D$.

Since an inter-domain handoff implies that an intra-domain handoff also occurs, i-j represents the number of pure intra-domain handoffs. Therefore, the AAA cost of the MR authentication in the proposed AAA protocol when there are i intra-domain handoffs and j inter-domain handoffs can be computed as

$$C_{AAA}^{MR}(i, j) = (i - j) \cdot C_{intra}^{MR} + j \cdot C_{inter}^{MR} \quad (3)$$

where C_{intra}^{MR} and C_{inter}^{MR} are the costs for intra-domain AAA and inter-domain AAA operations. On the other hand, the AAA cost of the MR authentication without the localized AAA procedure is given by

$$C_{AAA}^{MR}(i, j) = i \cdot C_{non-local}^{MR} \quad (4)$$

where $C_{non-local}^{MR}$ is the cost for an AAA operation without the localized AAA procedure. Then, the average AAA cost of the MR can be expressed as

$$C_{AAA}^{MR} = \sum_i \sum_j C_{AAA}^{MR}(i, j) \cdot \alpha(i) \cdot \beta(j) \quad (5)$$

For the VMN's AAA cost, we consider the AAA cost incurred during the VMN is attached to the MONET. We assume that the VMN's attachment time is drawn from an exponential distribution with mean $1/\eta_A$. Let k be the number of inter-domain handoffs during the attachment time. Then, the PDF of k is given by

Table 2. Parameters for numerical results

Wireless weight	Number of ARs in a domain	λ_I	ε_A	D_1	D_2	D_3
10	49	1	1	2, 5, 10	2, 5	2, 5

Table 3. Message length (bytes)

Attendant Solicit	Attendant advertisement	AReq	ARep	AMR
52	84	116	120	172
AHR	AHA	AMA	AMLR	AMLA
144	136	166	180	152

$$\gamma(k) = \begin{cases} 1 - \frac{1}{\rho_A}[1 - f_D^*(\eta_A)] & k = 0 \\ \frac{1}{\rho_A}[1 - f_D^*(\eta_A)]^2 [f_D^*(\eta_A)]^{k-1} & k > 0 \end{cases}$$

where $\rho_A = \eta_A / \mu_D$. Hence, the AAA cost of the VMN when there are k inter-domain handoffs during the attachment time can be computed as

$$C_{AAA}^{VMN}(k) = k \cdot C_{AAA}^{VMN}, \quad (6)$$

where C_{AAA}^{VMN} is the cost for each VMN's AAA operation. Consequently, the average AAA cost of the VMN is expressed as

$$C_{AAA}^{VMN} = \sum_k C_{AAA}^{VMN}(k) \cdot \gamma(k) \quad (7)$$

In this section, we evaluate the effects of mobility and the distance between a foreign network and a home network on the AAA cost (i.e., $C_{AAA}{}^{MR}$ and $C_{AAA}{}^{VMN}$). The parameters and the size of each AAA message are shown in Tables 2 and 3, respectively, which are based on Calhoun et al. (2003) and Narten, Nordmark, and Simpson (1998). D_1, D_2, and D_3 represent the distances between the AAAL server and the $AAAH_{MR}$ server, between the MR and its HA, and between the $AAAH_{MR}$ server and the $AAAH_{VMN}$ server, respectively. Then, C_{intra}^{MR}, C_{inter}^{MR}, and $C_{non-local}^{MR}$ can be calculated by multiplying the corresponding message length and the distance. For the transmission over a wireless link, a weight value is used and it is set to 10 (Xie & Akyildiz, 2002). The number of subnets in a domain is 49. λ_I and η_A are normalized to 1.0 whereas μ_D equals $\mu_S / \sqrt{N}$ by the fluid flow model (Zhang, Castellanos, & Campbell, 2002), where N is the number of subnets in a domain.

As shown in Figure 8, the proposed AAA protocol has a smaller AAA cost than the non-localized AAA protocol. Also, it can be seen that C_{AAA}^{MR} increases as μ_S increases (i.e., as the subnet residence time of the MONET decreases). This is because the number of inter- or intra-handoffs is reduced when the mobility (i.e., μ_S) is low. Figure 8 also indicates the AAA cost variation for different

Figure 8. The AAA cost of an MR

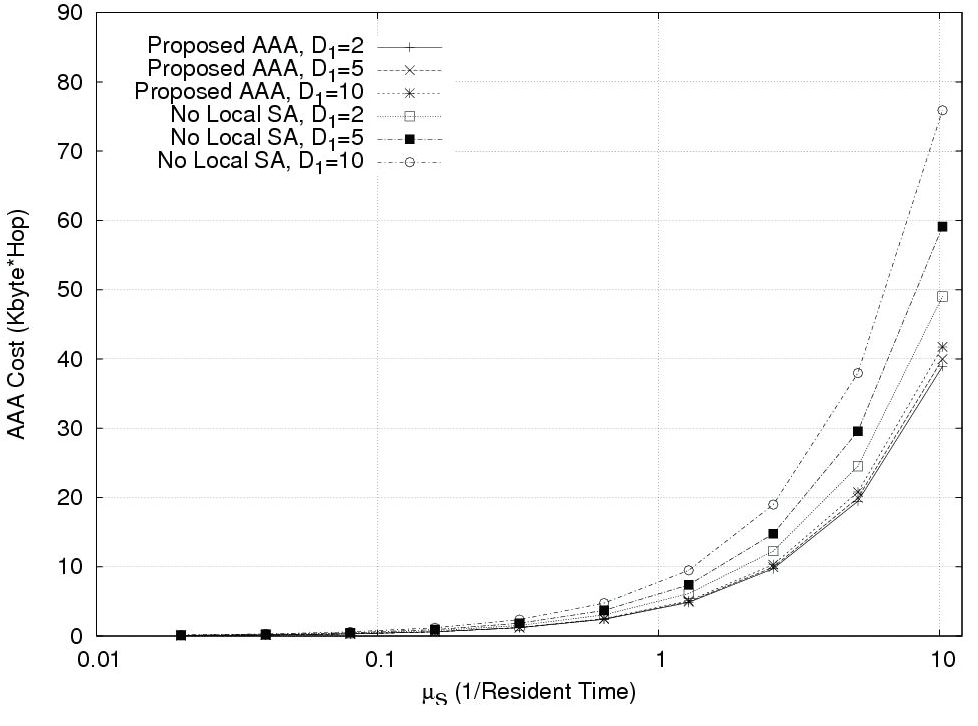
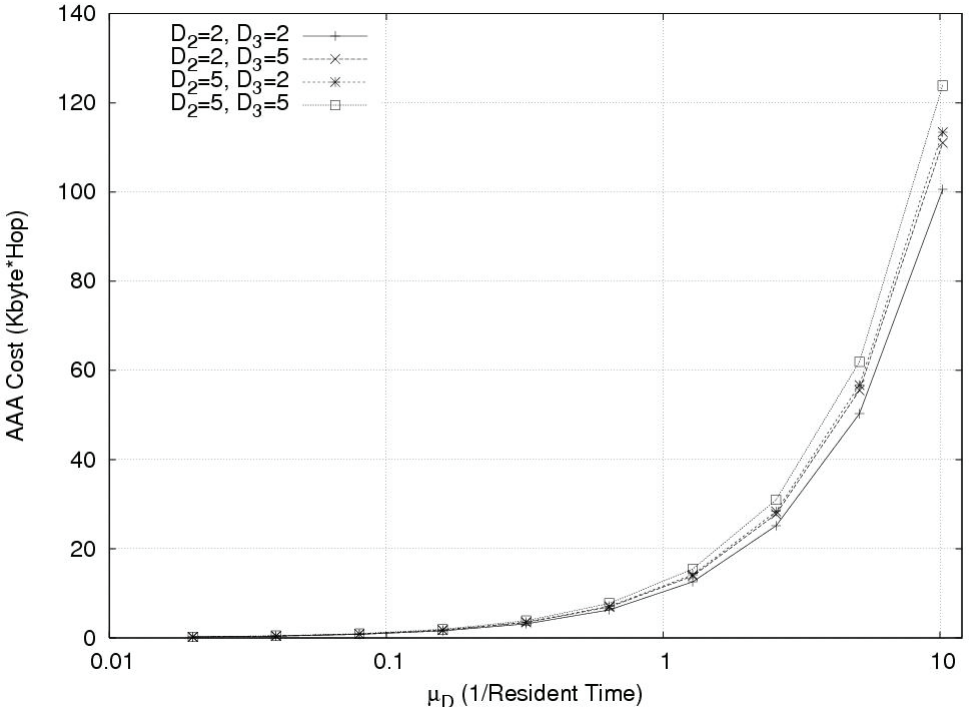


Figure 9. The AAA cost of a VMN



D_1 (i.e., D_1=2, 5, 10). Since C_{intra}^{MR} and C_{inter}^{MR} are proportional to D_1, C_{AAA}^{MR} increases with the increase of D_1 significantly. Especially, the effect of D_1 is more clear in the non-localized AAA protocol because an AAA procedure is always performed at the AAAH server in the non-localized AAA protocol. Therefore, it can be concluded that our protocol is more effective regardless of the distance between the home network and the foreign network. Note that this AAA cost considers only one MR. Hence, as the network mobility services are proliferated, the reduction of the AAA cost by the proposed AAA protocol will be more significant.

Figure 9 shows the AAA cost of the VMN, which exhibits a similar trend to Figure 8. It can be seen that the AAA cost when (D_2, D_3) is (5,2) is higher than the AAA cost of (2,5). This is due to IP-in-IP packet tunneling overhead between the MR and its HA. Namely, as the distance between the MR and its HA D_2 increases, more tunneling overheads incur and then the AAA cost also increases. As similar to Figure 9, the AAA cost of the VMN in our protocol is not highly affected by the distance values. Therefore, it is concluded that out protocol is less sensitive the distance between the home network and the foreign network.

CONCLUSION

In this chapter, we have proposed a localized AAA protocol in NEMO environments. The proposed AAA protocol is consistent with the NEMO basic support protocol where the mobility transparency is supported. The proposed AAA protocol introduces a shared key between the MR and the AAA server in the foreign network, so that the AAA procedure for the MR in intra-domain handoffs can be localized. In addition, we proposed a flexible billing mechanism for VMNs moving across different domains. We analyzed the security concerns in the proposed AAA protocol in terms of mutual authentication, key exposure, replay attack, and

man-in-the-middle attack. Performance evaluation results reveal that the localized AAA procedure can reduce the AAA traffic significantly and the localized AAA procedure is less sensitive to the distance between the home network and the foreign network. Consequently, it is expected that the proposed AAA protocol can be widely employed in NEMO environments.

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KEY TERMS

Accounting: Accounting is the action of tracking the consumption of network resources by users.

Authentication: Authentication is the action of confirming that a user who is requesting services is a valid user of the network services requested.

Authorization: Authorization is the action of granting the specific types of service to a user depending on the authentication.

Internet Engineering Task Force (IETF): IETF is an organization to develop, promote, and standardize Internet-related protocols.

Man-in-the-middle Attack: Man-in-the-middle attack is an attack in which an attacker is able to read, insert, and modify messages between two communication parties.

Network Mobility: Network mobility is the mobility of an entire network that changes its point of attachment to the Internet as a single unit.

Replay Attack: Replay attack is an attack in which a valid data transmission is maliciously or fraudulently repeated or delayed.

END NOTE

[1] In the NEMO basic support protocol, all packets destined to MNNs are tunneled at the MR's HA, so that the MR's HA can keep track of network usages of individual LFNs and VMNs. Therefore, the MR's HA can report this information to the AAAH server.

Section III
Security in Ad Hoc and Sensor Networks

Chapter XXVI
Security in Mobile Ad Hoc Networks

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ABSTRACT

Mobile ad hoc network (MANET) is a self-configuring and self-maintaining network characterized as dynamic topology, absence of infrastructure, and limited resources. These characteristics introduce security vulnerabilities, as well as difficulty in providing security services to MANETs. Up to date, tremendous research has been done to develop security approaches to MANETs. This work will discuss the existing approaches that have intended to defend against various attacks at different layers. Open challenges are also discussed in the chapter.

INTRODUCTION

A mobile ad hoc network (MANET) is a self-configuring and self-maintaining network composed of mobile nodes that communicate over wireless channels (Perkins, 2001). MANETs are characterized as infrastructure-less with rapid topology change, high node mobility, and stringent resource constraints. A MANET is usually used in situations such as military battles, disaster recovery, and emergent medical situations. While applications in these areas still dominate the research needs for MANETs, commercial applications (such as home networking and personal area networks) have also been brought to attention with the rapid research progress in mobile telephony and personal digital assistants.

Early research in MANETs assumed a cooperative and trusted environment, which unfortunately is not always true. In an unfriendly environment, a variety of attacks can be launched, ranging from passive eavesdropping to active interference. The attacks could target a number of devices or services in MANETs, such as wireless channels, routing protocols, high-level applications, or even security mechanisms themselves. A misbehaving node can be *selfish* or *malicious*, based on their intensions. A selfish node can simply deviate

from network protocols in order to maximize its own profit, while a malicious node may intend to corrupt some services or bring down some other nodes. Both selfish and malicious misbehaviors are dangerous in that they could cause degradation in the network performance, or even paralyzation of the entire network. Therefore security has become a primary concern, especially for security-sensitive applications in a noncooperative or hostile environment.

However, introducing security features to MANETs is not a trivial task. The lack of a fixed infrastructure determines that MANETs do not have a clear physical line of defense, unlike their wired counterparts, who can deploy security defense mechanisms (e.g., firewalls) at network devices such as gateways or routers. The decentralized manner of operations also implies that a central administration point is not realistic for MANETs. Moreover, all security services come with a price. The security mechanisms will share with other services the precious communication and computation resources, which may consequently affect the performance of the node, or even the entire network. Performance is also a basic concern for ad hoc networks, which means a tradeoff has to be made between security and other services such as computation and communication. Therefore, minimum consumption of resources is one of the most important requirements for security solutions in MANETs.

This chapter will discuss security issues in MANETs, including security attacks, security requirements, security solutions, and their advantages and weakness.

The remainder of this chapter is organized as follows: the following section will discuss the security vulnerabilities, security services, and security challenges for MANETs; the third section will focus on the security solutions that have been proposed for MANETs. The security mechanisms to protect MAC (medium access control) layer communications and routing protocols will be described. Intrusion detections, authentication, and key management will be also discussed in this section. In the last section we will discuss the open research issues for MANET security and then we will conclude the chapter.

VULNERABILITIES, SECURITY SERVICES, AND CHALLENGES

MANETs Vulnerabilities

MANETs suffer from all the vulnerabilities that their wired counterparts encountered. An adversary may launch various attacks ranging from *passive* eavesdropping to *active interference* such as traffic jamming, packet modification and fabrication, message replay, denial-of-service (DoS), and so forth. Some of these vulnerabilities are aggravated in a wireless context due to the characteristics of MANETs, such as the lack of a clear line of defense and the in-the-air communications.

Besides, ad hoc networks are susceptible to vulnerabilities that are inherent to wireless networks, which reside in their routing and autoconfiguration mechanisms. The MAC (medium access control) protocols (such as IEEE [1999] 802.11 series) and most of the routing protocols for MANETs are designed with the assumption that all the nodes will cooperate and would not intentionally deviate from the protocols. However, this is not always true, especially in an autonomous network where nodes belong to different self-profited organizations.

Eavesdropping is generally easier in MANETs than in the Internet due to the open nature of the communication medium in MANETs. Passive attacks are by nature difficult to detect, not mentioning in MANETs where many mobile devices support promiscuous mode. Like in the wired networks, cryptographic operations are used to prevent ad hoc networks from eavesdropping.

The MAC protocols in MANETs are vulnerable to traffic jamming, which is caused by nodes who fail to follow the protocols in order to maximize their own profit or simply to disrupt network operations. A node can obtain an unfair share of the bandwidth by transmitting without waiting its turn, or interrupt signal transmissions by injecting bogus signals into the network. Communication channels in MANETs are open and shared, therefore it is difficult to prevent and detect this kind of attacks. Moreover, ad hoc nodes are usually battery-powered, which makes energy a precious resource in MANETs. An adversary could launch a new type

of DoS attack, namely "sleep deprivation torture" attack (Stajano & Anderson, 1999), by forcing a node to relay packets.

Ad hoc routing requires the participation of all the nodes in the network. MANETs are *peer-to-peer*, namely all the nodes play the same roles as end hosts and routers as well. However, some selfish nodes may refuse to forward data packets or routing requests for other nodes to save energy or communication resources. Some more dramatic attacks by malicious nodes include dissemination of false routing information, sending frequent routing updates to achieve denial-of-service, and deviating traffic from legal route.

Like in the traditional wired networks, attacks can target the security mechanisms as well. For examples, cryptographic operations can be at risk if a secret key is intercepted and compromised, or a trusted authority is brought down. These attacks are not intrinsic to wireless networks, but they are difficult to prevent and detect in the context of MANETs.

Security Services

The services that should be provided in MANETs are the same as those in the wired networks, which include *availability*, *authentication*, *integrity*, *confidentiality*, and *nonrepudiation.*

- **Availability** ensures that network services are provided as supposed to be. In an ad hoc network without protection of proper security mechanisms, its service performance and availability can be easily compromised. For example, signal jamming at the physical and media access control layers can seriously interfere with communications or even bring down the physical channels. A malicious or selfish node can also disrupt routing services, which may result in network partition. To solve the problem, some economic models have been proposed to stimulate cooperation among nodes. Monitoring techniques are also used to ensure proper provision of network services. For instance, a node in promiscuous mode can monitor the communications in the vicinity.
- **Authentication** ensures that the identity of a node in communication is indeed the entity it declares to be. Authentication can prevent identity masquerade and unauthorized access to resource or information. Authentication is usually provided by digital signature or possession of a secret (such as a key). Due to stringent resource constraint of MANETs, the authentication protocols for the traditional Internet are not applicable because these protocols consume too much computational resources. Some authentication approaches that use one-way hash function, which proves to be faster than other cryptographic operations, have drawn much attention because of their efficiency.
- **Integrity** ensures that a message in transmission has not been maliciously altered or corrupted. A message can be corrupted due to presence of malicious attacks, or communication failures, which may be common on the lossy channels of ad hoc networks. In addition to the traditional approaches for the Internet, some researchers proposed that a node could perform integrity check by overhearing the next hop when this next hop forwards the packet on along the path. This overhearing technique can be easily used in ad hoc networks because of the open nature of the communication channels.
- **Confidentiality** guarantees that sensitive information is not disclosed to unauthorized entities. Encryption used in wired networks is also used for MANETs.
- **Nonrepudiation** ensures that the origin of a message cannot deny having sent the message. Nonrepudiation allows a malicious node who has sent false information to be accused by legitimate users, and therefore is important in intrusion detection. Asymmetric key cryptography has been used to provide nonrepudiation for both the Internet and MANETs.

Other security services for MANETs include *authorization* and *accounting.* But to our best of knowledge, not much research work has been pub-

lished on authorization or accounting especially for MANETs.

Security Challenges

Security is an important issue for mobile ad hoc networks, especially for those in security-sensitive environments. However, the unique characteristics of MANETs, such as absence of infrastructure, rapid and unpredictable change of topology, open and shared wireless medium, and stringent resource constraints, have posed nontrivial challenges to security designs.

First, use of open shared medium makes an ad hoc network susceptible to attacks such as eavesdropping, signal jamming, impersonation, message distortion, and message injection. A malicious node is able to impersonate other nodes even without gaining physical access to the victims.

Second, absence of infrastructure and frequent change of topology and membership has tremendously raised the probability of a network being compromised. Unlike the traditional wired networks, MANETs do not have dedicated routers to form a clear line of defense where traffic monitoring or access control mechanisms can be deployed. In addition, each mobile node functioning as a router and participating in routing and packet forwarding may lead to significant vulnerability since a malicious node en route can tamper the routing and data packets. In an ad hoc network, it is also difficult to introduce a central administrative entity to security solutions in that such an entity can easily become a target of attacks, which may then cause a failure of the entire network.

Third, due to constraints of resources (such as power, bandwidth, CPU capacity and memory), security mechanisms for MANETs must be lightweight in terms of communication overhead, computation complexity, and storage overhead. Asymmetric cryptography is usually considered too expensive for MANETs. Therefore symmetric cryptographic algorithms and one-way functions are commonly used to protect data integrity and confidentiality.

Last, an ad hoc network may consist of a great number of nodes, which renders *scalability* another main concern for security solutions.

The security mechanisms or approaches should be adapted to the characteristics of MANETs. Yang, Luo, Ye, Lu, and Zhang (2004) propose that the security solutions for MANETs should accommodate the following needs. First, the prevention and detection mechanisms should be fully distributed through the network. They should collect security information from individual nodes to secure the entire network. The security devices on each node are able to work alone in local prevention and detection with limited computational resources and battery power. Second, the security mechanism on different layers of the protocol stack should all cooperate and contribute to a line of defense. Also, all the three components of intrusion prevention, detection, and response, should be used to provide security. Finally, the security solutions should be able to adapt to the highly dynamic topology. It is difficult to accommodate these needs.

SECURITY SOLUTIONS FOR MANETS

Several security techniques or mechanisms have been commonly used to provide security features to MAC layer and ad hoc routing.

Digital signature can protect integrity of data packets or nonmutable fields in routing packets. However, public key cryptography is much slower than symmetric key cryptography, especially on devices with limited resources (such as CPU power and memory space), and has been considered unacceptable for MANETs by many researchers. Moreover, it is vulnerable to DoS attacks of flooding network with bogus packets for which signature verification is required. But public key cryptography is still adopted in many security mechanisms because of its superiority in key distribution and its effectiveness in providing integrity and nonrepudiation services.

Hash function is much faster than public key cryptography and therefore well suits the requirement of low overhead for MANETs. Hash chain is usually used to protect authentication for mutable fields in neighboring communications. Hash chain

is built by applying a one-way hash function repeatedly. To create a one-way hash chain, a node should choose a random value and then generate a list of hash values, $h_0, h_1, h_2, ..., h_n$, from the random value, where $h_{i+1} = H(h_i)$ for $0 \leq i < n$, where H is the hash function. To use a one-way hash chain for authentication, h_n should be distributed first. Consecutive element, h_i, can be authenticate by applying H to previously distributed element, h_j ($j > i$), for (j - i) times.

Monitoring technique has been proved an effective way to provide availability to routing advertisement or data packet forwarding, and to promote fair share of bandwidth at MAC layer. To monitor, nodes turn on *promiscuous* mode to listen to communication of neighboring nodes in order to ensure proper transmission of frames or packets.

Reputation mechanisms have been used together with *cooperatio*n mechanisms to enhance security in routing and MAC layer protocols. It will be discussed in "Cooperation" topic in a later section.

Wireless MAC Security

MAC protocols for wireless networks such as IEEE 802.11 (1999) use a contention resolution mechanism for sharing the open communication channel. This resolution mechanism is fully distributed and requires cooperation among all the participating nodes. The participating nodes are expected to perform a random *backoff* before transmission to reduce contention and to ensure a reasonably fair share of the channel.

However, in an untrusted network environment where selfish or malicious nodes may be included, cooperation cannot always be guaranteed. A *selfish* node may intentionally deviate from MAC protocols to maximize its throughput by obtaining an unfair share of the bandwidth. A *malicious* node may intend denial-of-service (DoS) attacks by injecting frames on the wireless medium continuously, or intermittently with the intention of conserving its own energy. The injection may cause radio collisions and transmission jamming, and thus repeated backoffs among legitimate nodes. A malicious node can also transmit strong noise signals to prevent messages in the victim vicinity from being received.

No matter a node is selfish or malicious, the consequences of their misbehaviors can be severe and disastrous, and therefore should be addressed as security problems with essential concerns. The security solution is to detect misbehaviors and to locate the misbehaving nodes in a timely and reliable manner. This is not a trivial task due to the random nature of the MAC protocols and the shared and volatile medium. It is especially difficult to differentiate between misbehavior and an occasional deviation caused by impairment of wireless link.

Several approaches have been proposed to handle selfish and malicious misbehaviors at the MAC layer[1].

One approach is to address selfish misbehaviors by using game theoretic techniques to find a state where the misbehaving nodes cannot gain any advantage over the well-behaved nodes (Cagalj, Ganeriwal, Aad, & Hubaux, 2004; Konorski, 2001, 2002; Mackenzie & Wicker, 2000, 2003; Michiardi & Molva, 2002b). This approach has also been used at network layer to secure routings.

Konorski (2001, 2002) proposes a game theoretic model that targets *selfish* nodes who fail to adhere to MAC protocols by waiting for smaller backoff intervals than supposed to be. By applying the noncooperative game model (Jones, 2000), the approach modifies the backoff algorithm using blackbursts and leads the game to a Nash equilibrium point (Nash, 1950). The approach requires accurate measurement of the duration, which is difficult to grant in MANETs. Cagalj et al. (2004) developed a strategy that employs two Markov chains (Jha, Tan, & Maxion, 2001) to derive from contention windows the access possibilities of the misbehaving nodes and the well-behaved nodes, respectively. The approach can reach the Nash equilibrium with multiple selfish nodes.

Another approach, which has been mostly used, is to monitor the neighboring node by overhearing and then penalize the identified misbehaving nodes (Gupta, Krishnamurthy, & Faloutsos, 2002; Kyasanur & Vaidya, 2005; Radosavac, Baras, &

Koutsopoulos, 2005; Radosavac, Cardenas, Baras, & Moustakides, 2006; Raya, Hubaux, & Aad, 2004; Xu, Trappe, Zhang, & Wood, 2005).

Raya et al. (2004) deals with MAC misbehaviors in wireless hot-spot communities, such as intentionally scramble frames or illegal manipulation of backoff intervals also. A sequence of observations is required to detect misbehaviors based on the extent to which MAC protocol parameters are manipulated.

Kyasanur and Vaidya (2005) propose modifications to IEEE 802.11, such as letting the receiver of the particular transmission decide whether the sender has deviated from the protocol. It is proposed to use additional nodes in the vicinity to detect collusions between the receiver and the sender. The authors also present a diagnosis scheme, which uses a moving window and thresh to capture the misbehaving nodes. A scheme for punishing a selfish node is also presented. Simulation results show that the detection and penalty schemes are effective in handling selfish MAC misbehaviors.

Radosavac et al. (2005) propose to let a node compute the backoff values of its neighboring node based on the RTS (request-to-send), CTS (clear-to-send), or ACK (acknowledgement) messages. The problem is cast into a "minimax robust detection framework," in which the worst-case instance of attack will be identified and a detection rule of optimum performance is generated with uncertain information. The approach requires clock synchronization, which is considered not realistic by some researchers. A recently published work by Radosavac et al. (2006) is an advanced version of the published work of Radosavac et al. in 2005. The work studies the single-node attacks as well as colluding attacks.

Gupta et al. (2002) and Xu et al. (2005) studied the DoS attacks at MAC layer and analyzed different attack models with their traffic patterns. Gupta et al. (2002) demonstrate simulation of IEEE 802.11 protocol as well as emulation of a perfectly fair MAC (FAIRMAC) protocol in order to show how the employment of MAC layer fairness can prevent or alleviate the effect of the DoS attacks. The authors also show that many other factors such as location of the malicious node, availability of other compromised nodes, availability of routing information, together with the fairness, determine the efficacy of the DoS attacks. Xu et al. (2005) also provide interesting insights into jamming attacks at MAC layer. They proposed four jamming attack models that can be used by an adversary who intend DoS attacks: *constant*, *deceptive*, *random*, and *reactive jamming.* The effectiveness of the four jammer strategies is evaluated by implementation of a prototype using Berkeley Motes platform. Different measurements for detecting jamming attacks are proposed. The authors found that not a single measurement is sufficient to conclusively differentiate malicious attacks from link impairment.

To reliably detect misbehaviors at MAC layer, accurately and reliably monitoring the transmission pattern from a node is a critical factor and still worth further investigation.

Secure Routing Protocols

Routing protocols for MANETs are very different from those existing Internet protocols, because MANETs are self-organized and the protocols need to cope with frequent topology change, open shared medium, and resource restrictions. In addition, all the nodes also serve as routers, participating in route discovery, route maintenance, and packet delivery. These characteristics have introduced significant difficulty to routing security in MANETs.

In 1996, The Internet Engineering Task Force (IETF) established a MANET workgroup (Macker & Chakeres, 2006), which goal is "to standardize of the IP routing protocol functionality suitable for wireless routing applications." Since then, some routing protocols have been proposed particularly for MANETs.

AODV (ad hoc on-demand vector) (Perkins, Belding-Royer, & Das, 2003) is a reactive routing protocol. In AODV, the node who needs to establish a route to another node will broadcast a route request (RREQ) message to its neighbors. Each node that receives the message establishes a reverse link toward the originator of the RREQ, unless such a link has already existed. *Dynamic*

source routing (DSR) (Johnson, Maltz, & Hu, 2004) is a protocol that uses *source routing* technique, in which the sender constructs a "source route" in the packet's header that gives the hosts on the path. *Destination-sequenced distance-vector* (DSDV) (Perkins & Bhagwat, 1994) is a proactive routing protocol which maintains a routing table that lists all possible destinations in the network as well as metric and next hop to the destination.

These protocols are designed without security concern in mind, and therefore are susceptible to various attacks.

Attacks on MANET Routing

A selfish or malicious node can disrupt routing services *passively* or *actively*. Their purposes include selfish conservation of own resource, disruption of routing, excessive resource consumption, and so forth.

A selfish node may refuse to participate in routing by simply discarding routing packets. This attack is usually not defended against secure routing protocols in that the node can still fail to forward data packets even if a path including the selfish node has been established. To prevent this attack, some cooperation mechanisms have been proposed, which will be discussed later.

A malicious node can maliciously advertise falsified routing information by tampering fields such as source, destination, metric, and so forth. For example, an attacker can claim falsified short distance information by advertising zero or a very small metric in order to attract and later drop the traffic originally destined to other nodes (*blackhole* attack), or in order to include itself on the path so that it can analyze the communications. Another example is that an attacker can use forged routing packets to create a routing loop, causing packets to circulate in the network without reaching their destinations. This malicious attack should be distinguished from nodes unknowingly providing incorrect or obsolete routing information, which may result from topology change. This is not a trivial task due to the nature of ad hoc networks.

Another type of attack, *wormhole* attack (Hu, Perrig, & Johnson, 2003a), happens when two malicious nodes establish a link via private network connection and forward all the received traffic to each other. In this type of attack the normal flow of routing packets will be short-circuited, and a virtual vertex cut of nodes can be created in the network that the attackers control.

An adversary can also mount a *replay* attack by sending an old advertisement in an attempt to get other nodes to update its routing table with stale routes. Sequence number is usually used to prevent packets from being repeatedly passed on.

Denial-of-service (DoS) attack can be attempted by injecting packets into the network which may cause excessive consumption of resources. One special type of DoS attacks, *jellyfish attacks* (Aad Hubaux, & Knightly, 2004), is to hold packets unnecessarily for some amount of time before forwarding them. The jellyfish attack can cause high end-to-end delay and delay jitter. *Rushing attacks* (Hu, Perrig, & Johnson, 2003b) takes advantage of the suppression mechanisms that are used by on-demand routing protocols to prevent duplicate routing requests from being spread. The suppression mechanism processes only the first request while skipping the duplicate ones. All these attacks are difficult to detect in MANETs due to the inherent volatility of the communication channels.

Besides failing to follow routing protocols, which is sometimes referred as *routing attacks*, an attacker may also target the data messages traversing an established path. A misbehaving node may maliciously alter or drop data packets in transit, which is called *packet forwarding attacks*. These two types of attacks are different due to the differences of routing and data packets. Usually, routing packets are altered as they circulate around the network (such as in *metric* field that states the shortest distance to destination). Thus routing packets are *mutable*, and called *hop-by-hop* transmission. The data packets are *nonmutable*, because the data are not changed during transmission (except for some particular fields in the header) and therefore is *end-to-end* transmission. The integrity of the data packets can be protected by traditional cryptographic operations, while routing packets are hard to protect.

Secure Routing Protocols

Sanzgiri, Dahill, Levine, Shields, and Royer (2002) propose the authenticated routing for ad hoc networks (ARAN), which is a secure protocol that provides authentication and nonrepudiation to route discovery and maintenance. ARAN requires that each node have a certificate signed by a trusted certificate server. It introduces much overhead by requiring every node that forwards route request to sign the certificate, and therefore is vulnerable to DoS attacks.

Papadimitratos and Haas (2002) propose the secure routing protocol (SRP), which can be applied to DSR. SRP requires a security association between the source and destination nodes and uses the association to authenticate route request and route reply messages. Malicious modifications of the routing messages will be detected at the destination. SRP does not attempt to secure route error messages, therefore the messages are subject to forgery.

Ariadne was developed by Hu, Johnson, and Perrig (2002) based on DSR. Ariadne can authenticate routing messages using one of the three schemes: shared secret keys between all pairs of nodes, shared secret keys between communicating nodes combined with broadcast authentication, or digital signatures. Ariadne uses symmetric cryptography primitives, with TESLA(timed efficient stream loss-tolerant authentication) (Perrig, Canetti, Song, & Tygar, 2001; Perrig, Canetti, Tygar, & Song, 2002), a broadcast authentication scheme that requires time synchronization. Some researchers argue time synchronization is an unrealistic requirement for ad hoc networks.

Hu, Perrig, and Johnson (2002) designed a secure efficient ad hoc distance vector routing protocol (SEAD) for DSDV to prevent from attacks of DoS, replay attacks, and wormhole attacks. SEAD also uses hash chains to authenticate metric and sequence numbers. SEAD does not use asymmetric cryptography operations thus the authentication overhead is maintained at a reasonable level.

Zapata (2006) proposed secure AODV (SAODV). SAODV is a secure extension of the AODV routing protocol that can be used to protect the route discovery. SAODV uses a digital signature to authenticate in an end-to-end manner and to protect the integrity of the nonmutable fields in routing messages (such as source, destination, sequence number, etc.). Hash chain is used to authenticate in a hop-by-hop manner the hop-count information, which is the only mutable field in the messages. A signature extension is added to the original AODV RREQ and RREP messages for authentication with signature and hash chain.

Hu et al. (2003) also designed a mechanism, called *packet leash*, to defend against wormhole attack. However, the mechanism requires clock synchronization. Song, Qian, and Li (2005) therefore proposed a statistical approach that eliminates the need of clock synchronization. An approach to defend against rushing attacks has also been proposed (Hu et al., 2003).

Cooperation in MANETs

The presence of selfish nodes that do not respect the routing protocols or MAC protocols can cause performance degradation or even network partition. This subsection will discuss the approaches that have been proposed to solve this problem. Most of these approaches are used at the network layer, but some approaches can also be applied to MAC layer with proper modifications.

1. **One of the approaches is to detect misbehaving nodes and then avoid such nodes in routing.**

Marti Giuli, Lai, and Baker (2000) propose two techniques, *watchdog* and *pathrater*, to detect the presence of nodes that have agreed to forward packets but fail to do so. The watchdog, run by each node on a path, can identify the misbehaving node by monitoring the next hop to ensure that the packets are timely passed on. Although it can detect misbehaviors at the forwarding level, the watchdog might not be able to detect in the presence of collisions, colluding attacks, and partial dropping. The pathrater can help to avoid the misbehaving nodes. Each node maintains a rating for every other node in the network. The rating will be incremented if the node is on an actively used

path, and decremented on a broken path. A node calculates a path metric by averaging the node ratings in the path.

2. **Another approach is to design protocols that stimulate cooperation by penalizing misbehavior or rewarding behavior of forwarding for other nodes' benefit.**

Buttyan and Hubaux (2000, 2003) propose a protocol that can stimulate packet forwarding. It requires a node to pass all packets to its security module, which maintains a counter called *nuglet counter*. The counter is decreased whenever the node sends a packet as the originator, and increased when the node forwards a packet for another node. Since the value of the counter must remain positive, a node needs to maintain a balance on the counter by forwarding packets for the benefits of others to have its own packets to be sent. To prevent a node from illegitimately increasing its own counter, the counter is required to be maintained by a trusted and tamper resistant hardware module (such as a Smart card).

CONFIDANT (cooperation of nodes fairness in dynamic ad-hoc networks) (Buchegger & Boudec, 2001, 2002a, 2002b) was proposed to detect, discourage and stop selfish misbehaviors. CONFIDANT consists of four components: a *monitor* to observe the neighborhood; a *trust manager* to deal with incoming and outgoing warning messages; a *reputation system* to maintain reputation records based on own experiences, vicinity observations, and reported records; and a *path manager* for nodes to adapt their behavior according to the reputation of a node or a path. CONFIDANT takes into consideration the problem of nodes providing false information to gain good reputation. With a proper weight system and a modified Bayesian estimation procedure, the second-hand information can still speed up the detection while suppressing false positives and negatives. The simulation results show that the network performance can still be good even when half of the network population misbehaves.

CORE is a collaborative reputation mechanism (Michiardi & Molva, 2002a). Similarly to CONFIDANT, CORE also differentiates between observations and reports by other nodes. It applies different weights to subjective reputation (observations), indirect reputation (positive reputation reported by others), and functional reputation (the subjective and indirect reputation calculated with respect to different functions). At each node, reputation values are stored in a reputation table, and a watchdog mechanism is used to detect misbehaving nodes.

Sprite is a cheat-proof and credit-based system (Zhong, Chen, & Yang, 2003), which also requires that nodes receive enough credits by forwarding for other nodes to send their own packets. To prove a node has received or forwarded a message, the node keeps a receipt of the message and uploads the receipt to a credit clearance service (CCS). To motivate nodes to report receipts, CCS gives more credits to a node that forwards a message than to a node that does not. Proper actions are taken to prevent the cheating action. If a message is not received by the destination, the credits to the intermediate nodes will be greatly reduced, and therefore the benefit of falsely reporting a receipt by an intermediate node will be reduced too. The approach needs a centralized trusted entity, which is hard for MANETs.

Some other interesting approaches that use punishment or rewarding systems can be found by Mohan and Joiner (2004) and Salem, Buttyan, Hubaux, and Jakobsson (2003).

3. **Game-theoretic techniques (Jones, 2000) have also been used to develop protocols for stimulating cooperation (Anderegg & Eidenbenz, 2003; Srinivasan, Nuggehalli, Chiasserini, & Rao, 2003).**

These techniques assume that all nodes are selfish and *rational*, that is, they only do things that are beneficial to themselves and their purpose is to maximize their own utility. Usually *noncooperative* game model is used in these approaches. By means of imposing suitable costs on network operation, the game reaches a stable state called "Nash equilibrium" (Nash, 1950), where a selfish node cannot gain an advantage over well-behaved nodes.

Anderegg and Eidenbenz (2003) provide a game theoretic approach, which goal is to achieve truthfulness and cost-efficiency for routing protocols in MANETs. The approach pays the forwarding nodes a premium over their actual costs for forwarding data packets. The authors show that the total overpayment is relatively small.

Although protocols developed with game-theoretic techniques may be resilient to misbehavior, they may not achieve the same performance of protocols developed under the assumption that all nodes are well-behaved.

Authentication and Key Management in MANETs

Authentication and key management are essential problems for MANET security.

Authentication in MANETs

Up to date, a number of authentication protocols have been proposed for MANETs (Balfanz, Smetters, Stewart, & Wong, 2002; Lu & Pooch, 2005; Perrig, Canetti, Tygar, & Song, 2000; Venkatraman & Agrawal, 2000; Weimerskirch & Thonet, 2001).

Stajano and Anderson (1999) propose an approach for ad hoc network of wireless devices: *secure transient association*. The purpose of the approach is to provide transient association between the controller and the peripheral, which is essential for ad hoc authentication. The idea came from the biology fact that a duckling emerging from its egg will recognize the first moving object it sees as its mother. Similarly, the approach defines that a device will recognize the first entity that sends it a secret key as its owner. As soon as this ownership has been established, the relationship will last for the rest of the nodes' life.

Perrig et al. (2001, 2002) propose a broadcast authentication scheme, TESLA, which uses a one-way key chain with delayed key disclosure. TESLA first bootstraps an authentic key from a one-way key chain between the sender and its receivers, and then broadcasts authentications with delayed key disclosure. The delayed key disclosure can prevent a malicious node from tampering a node that has delays in receiving the newest key, by means of using the newest key to forge packets with valid authentication information. Authentication techniques that use one-way hash chain keys can tolerate packet loss and have the advantage of low overhead. TESLA has been adopted by many approaches to authenticate *neighboring communications* in MANETs.

Zhu, Xu, Setia, and Jajodia (2003) propose a light-weight hop-by-hop authentication protocol (LHAP), in which every node authenticates all the packets received from neighbors before forwarding it. LHAP also uses one-way hash chain, like TESLA, but it does not use delayed key disclosure. LHAP uses TRAFFIC chain (a one-way hash chain) to authenticate packets, and uses TESLA chain to authenticate TRAFFIC keys. Security properties and performance is analyzed. The analysis shows that LHAP is lightweight and practical.

Key Management in MANETs

Key management is an essential cryptographic primitive that is the basis of the other security primitives. In the traditional wired networks, centralized key management approaches are usually used. However, an ad hoc network is peer-to-peer and does not have a central administration point. In addition, a central authority may become a single point of failures in case of heavy workload, as well as an easy target of malicious attacks. Therefore, recent research has been focused on looking for key management approaches that are not only efficient, but also well functional on a dynamic network topology, and tolerant to link failures.

A partially or fully distributed certificate authority is commonly used for key management in MANETs.

Zhou and Haas (1999) propose a fully distributed public-key management service for ad hoc networks. It is assumed that the communication channels are reliable, and all nodes in the system know the public key and trust any certificates signed using the corresponding private key. A $(n, t + 1)$ t*hreshold cryptography* scheme is used

for distribution of the private key, where the key is divided into *n* shares. Therefore, *n* parties are allowed to share the ability to perform a cryptographic operation (e.g., creating a digital signature), and any $t + 1$ parties can perform the operation jointly. To sign a certificate, each server produces a partial signature for the certificate using its share and submits the partial signature to a combiner that can generate the entire signature. In this way, the system can tolerate a certain number ($t < n$) of compromised servers.

A similar approach proposed by Kong, Zerfos, Luo, Lu, and Zhang (2001) provide a more fair distribution by allowing *each* node to carry a secret share. Any $t + 1$ nodes in the vicinity of the requesting node can jointly provide complete service, which increases availability and scalability of the service. However, this scheme is not secure if an attacker can compromise arbitary $t + 1$ nodes and thus can collect enough shares and reconstruct the system's private key.

According to Zhou and Haas (1999) and Kong et al. (2001), a trusted authority is needed for initialization of the first $t + 1$, which is difficult in MANETs. In addition, it is still not clear how to determine the number *t* initially and adapt *t* based on *n*.

Capkun, Buttyan, and Hubaux (2003) propose a fully self-organized public-key management system that does not require use of any trusted authority even in the system initialization phase. Like PGP (pretty good privacy)(Zimmermann, 1995), the scheme allows a node to create public and private keys by itself. But the keys and certificates are not stored in centralized certificate repositories. Instead, they can be stored at the nodes in a fully distributed manner. When a node wants to obtain the public key of another node, it acquires a chain of valid public-key certificates. The first certificate of the chain can be directly verified by using a trusted public key. Then each sequential certificate can be verified using the public key contained in the previous certificate of the chain. The last certificate contains the public key of the target user. The system allows the nodes in the network to perform key authentication based only on their local information.

However, Chan (2004) argues that although some protocols are fully distributed and self-organized without needing any trusted third party (TTP), they are not robust to dynamic topology or sporadic links because they need the routing structure that has been established initially.

Chan (2004) proposes a distributed symmetric key management scheme for MANETs, which uses a fully distributed and self-organized key pre-distribution scheme (DKPS) without relying on TTPs or infrastructure support. The DKPS scheme has three phases, namely *distributed key selection* (DKS), *secure shared-key discovery* (SSD), and *key exclusion property testing* (KEPT). In the DKS phase, each node randomly picks keys from the publicly known universal set to form its key ring, in which *exclusion property* will be ensured to avoid collision. As soon as each node shares a common key with any other node, it enters the SSD phase and broadcasts its key identifiers to others. To guarantee that the nodes can let each other know which keys they are having in common without revealing the keys to others, the author proposes MRS (modified Rivest's scheme) and built SSD upon MRS. MRS is based on the work of Rivest, Adleman, and Dertouzos (1978), and is a special class of encryption functions that allow operations on the encrypted data without needing knowledge of the decryption functions. In KEPT phase, a node tests whether its set of keys satisfy the exclusion property.

Crepeau and Davis (2003) provide a certificate revocation scheme that can defend against attacks of maliciously accusing other nodes and using revoked certificate to access network services.

Many researchers are still making efforts to find a secure yet cost-efficient key distribution approach.

Intrusion Detection Systems (IDS) for MANETs

In the traditional Internet, network devices such as routers, switches, and gateways can be used to monitor the traffic. Due to the lack of these network devices and a fixed infrastructure, intrusion detection in MANETs is more challenging

than that in the Internet. Moreover, the restriction of resources again brings more difficulty to data analysis, which usually plays an important role in intrusion detection. A comprehensive survey on IDS for MANETs can be found by Avantvalee and Wu (2006).

An IDS for MANETs not only has the same requirements as in the wired networks (such as reliability, minimal false positive and false negative rates, transparency to system and users, etc.), but also requires low usage of system and network resources. Therefore, the design and development of IDS for MANETs is not a trivial task.

A simple solution for IDS in MANETs is that each host relies on itself for detection, where the audit data are gathered and processed locally. Some IDS proposed for MANETs use this solution of letting individual nodes to determine intrusions independently in case the local evidence is strong. But many systems also allow a node to request complementary information from others so that cooperation can be reinforced in case of weak or inconclusive local evidence.

Albers, Camp, Percher, Jouga, Me, and Puttini (2002) propose a local IDS (LIDS), which uses several mobile agents on each node. All the LIDS in a community can collaborate to alert each other of intrusions. These data are independent from operating system and need no additional resources for local information. A LIDS has several data collecting agents of different types: a *local agent* that locally detects intrusions and responds to intrusions; a collection of *mobile agents* that collect and process data from remote hosts; and a *local MIB agent* that collects MIB (management information base) variables for the mobile agents or the local LIDS agent. The implementation of prototypes was claimed by the authors, but the results are not demonstrated in the publication.

A distributed intrusion detection model was later proposed by Zhang, Lee, and Huang (2003). The model of the IDS agent is composed of six modules: a *local data collection module* that collects real-time audit data; a *local detection engine* that performs local anomaly detection; a *cooperative detection engine* that helps collaboration and collects broader data sets from other agents; a *local response module* that triggers local response actions; a *global response module* that coordinates responses among neighboring nodes; and a *secure communication module* that provides secure communication channels among IDS agents. On the anomaly detection model, two classification techniques, RIPPER(repeated incremental prunig to produce error reduction) and SVM (support vector machine) light, are applied to compute classifiers as anomaly detectors. The classifiers are used to detect anomaly updates to routing tables. The performances are evaluated and compared through simulations. The authors find that protocols with strong traffic correlation tend to have better detection performance.

Kachirski and Guha (2003) propose an agent-based IDS that uses multiple mobile sensors to determine intrusions. The system assigns functional tasks different agents: a *network monitoring* agent to monitor network packets (only on certain nodes to preserve resources); a *host monitoring* agent on every node to monitor system and applications level activities; a *decision-making* agent on every node to determine intrusions based on host-level information, and on certain nodes to determine network-level intrusions; and an *action* agent on every node to respond to intrusions. Similarly to the two IDS described above, this system makes intrusion decisions based on both independent and collaborative monitoring, and the level of the monitoring can be adapted according to the availability of the computational and network resources.

Another intrusion detection technique is the dynamic hierarchical intrusion detection architecture proposed by Sterne, Balasubramanyam, Carman, Wilson, Talpade, Ko et al. (2005). The system requires every node to monitor, log, analyze, and respond to detected intrusions. It also uses clustering to form a hierarchical structure. Different nodes (e.g., leaf nodes and clusterhead nodes in the structure) may perform different functions in intrusion detections. This hierarchical structure is advantageous in monitoring end-to-end traffic and thus can help detect end-to-end attacks. The system does not use promiscuous listening, which is arguably unrealistic for MANETs. However, some researchers have also argued that a hierarchi-

cal architecture may not be suitable to MANETs either, due to the rapid topology change of MANETs and the high overhead introduced by organizing the hierarchy.

Sun, Wu, and Pooch (2003) propose a zone-based IDS (ZBIDS). ZBIDS divides the network into nonoverlapping zones. The nodes are categorized into two types based on their locations to a zone: intrazone nodes (within a zone and not connected to nodes in another zone) and interzone nodes (within a zone and connected to nodes in another zone). Intrazone nodes are responsible for local detection and broadcast in case of alerts. Interzone nodes perform aggregation and correlation of these local detection results. The system can limit the detection cooperation in a zone, which may reduce the overhead by the broadcast and aggregation. However, the system requires that each node know its physical location, which needs prior design setup. The management of zones is not a trivial task either.

Intrusion detection has been a challenging task for MANETs, mainly due to the distribution nature and resource constraints of ad hoc networks. To determine intrusions with local or incomplete information and with low overhead has been a major concern for researchers.

OPEN CHALLENGES AND CONCLUSION

Challenges

The research in MANET security is still in its early stage. Some areas that are interesting but little explored include accounting, trust management, authentication, and key management.

Accounting provides the method for collecting the information used for billing, auditing, and reporting. Accounting mechanisms can track the services that users are accessing as well as the amount of network resources they are consuming. Accounting is a challenging problem due to the distributed and ephemeral nature of MANETs.

The characteristics of MANETs also bring difficulty to *trust management*. In MANETs, the trustworthiness is evaluated based on the information or evidence provided by peers, not by trusted authorities or a central administration point (as in the Internet or wireless networks with base-stations). Additionally, the gathering of the trust evidence may be difficult due to the small bandwidth, and therefore local information has to be relied on. Evaluation with uncertain and incomplete trust evidence certainly poses challenges to trust management.

Research progress has been made on authentication and key management. But finding cryptographic mechanisms that consume less computational resources and impose lower time complexity is still a major research concern in MANET security.

Another problem for MANET security is to find an effective and efficient approach for *intrusion response*. Many publications simply mentioned that proper actions should be taken to react to intrusions, which may include alarming the other nodes in the network, isolating the compromised nodes, or re-establishing the trust relationship for the entire network. But the problem of *how to* locate and then isolate the compromised nodes is not discussed in details. The location and isolation could be even more difficult when distributed attacks are launched from multiple sources. Eliminating the compromised nodes by rekeying or rebuilding the trust could be an effective solution. However, it is certainly not efficient taking into account the computation and communication overhead it may cause.

Some other unexplored research problems include the tradeoff between privacy (such as identity anonymity and location privacy) and other security services (such as accounting and intrusion detection), and the tradeoff between security strengths and network performance.

Yang et al. (2004) argue that MANET security needs a "multifence security solution," namely *resiliency-oriented* security design. They argue that the existing proposals are attack-oriented because the protocols target some specific attack that has been identified first. These protocols therefore may not work well in the presence of unanticipated attacks. They propose that a security solution is needed that can be embedded into every component or every layer in the network. The solution can

offer multiple lines of defense against many both known and unknown security threats.

Besides problems described above, how to adapt the security mechanisms in a large-scale wireless network is also an interesting problem. The scalability of security mechanisms and the compromise between security and network scalability are certainly topics worth further research study.

Conclusion

With the rapid proliferation of wireless networks and mobile computing applications, MANETs have received increased attention. Security is an important feature for ad hoc networks, especially in untrustworthy environments such as battlefields. Development of security solutions for ad hoc networks has therefore become a major research concern.

However, the characteristics of ad hoc networks have not only introduced vulnerabilities to malicious attacks varying from passive eavesdropping to active interfering, but also imposed difficulty and challenges in introducing security features to MANETs.

This book chapter has discussed the security vulnerabilities, challenges, and security solutions for MANETs. A variety of attacks and their countermeasures have been identified for different network operations, mechanisms, and network layers. Existing research efforts as well as the open challenges were discussed in the chapter.

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KEY TERMS

Authentication: The processes of verifying the identity of an entity if it is indeed the entity it declares to be.

Intrusion Detection: The techniques or processes of detecting inappropriate, incorrect, or anomalous activities.

Key Management: The techniques or processes of creating, distributing, and maintaining a secret key, which will be used to protect the secrecy of communications or to ensure the original data are not maliciously altered.

MANET (mobile ad hoc network): An infrastructure-less, self-organizing network of mobile hosts connected with wireless communication channels. A MANET does not have a fixed topology because all the hosts can move freely, which results in rapid and unpredictable topology change.

Medium Access Control (MAC): A sublayer of the data link layer specified in the seven-layer OSI (open systems interconnection) model. It addresses problems of moving data frames across a shared channel.

Routing: The process of selecting paths in a network along which to send data packets.

Security: The concepts, measures, or processes of protecting data from unauthorized access or disruption.

END NOTE

[1] Signal jamming can also be launched at physical layer, but it is not within the scope of this chapter because it is more related to electrical engineering than computer security.

Chapter XXVII
Privacy and Anonymity in Mobile Ad Hoc Networks

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ABSTRACT

Providing privacy is often considered a keystone factor for the ultimate take up and success of mobile ad hoc networking. Privacy can best be protected by enabling anonymous communication and, therefore, this chapter surveys existing anonymous communication mechanisms for mobile ad hoc networks. On the basis of the survey, we conclude that many open research challenges remain regarding anonymity provisioning in mobile ad hoc networks. Finally, we also discuss the notorious Sybil attack in the context of anonymous communication and mobile ad hoc networks.

INTRODUCTION

The quest for privacy in today's increasingly pervasive information society remains a fundamental research challenge. In the traditional (wired) Internet, one essential means for protecting privacy is *anonymous communication.* Being anonymous usually implies that a user remains unlinkable to a set of items of interest (e.g., communication partners, messages) from an attacker's perspective (Pfitzmann & Hansen, 2006). The capabilities of the attacker are usually modeled by an *attacker model*, which can, for instance, include a rogue communication partner or an observer tapping the communication lines. Further, more advanced applications can be deployed on top of anonymous

communication mechanisms, to, for instance, enable pseudonymous applications.

This chapter investigates how anonymous communication can be enabled in *mobile ad hoc networks* (Corson & Macker, 1999); networks constituted by mobile platforms that establish on-the-fly wireless connections among themselves and ephemera networks without central entities to control it. They are of great importance as they constitute a basic core functionality needed for deploying *ubiquitous computing*. In short, ubiquitous computing would allow for computational environments providing information instantaneously through "invisible interfaces," thus allowing unlimited spreading and sharing of information. If realized, ubiquitous computing could offer an invaluable support for many aspects of our society and its institutions. However, if privacy aspects are neglected, there is a great likelihood that the end product will resemble an Orwellian nightmare.

In this chapter, we study how privacy and anonymity issues are tackled today in mobile ad hoc networks by surveying existing anonymous communication mechanisms adapted for mobile ad hoc networks[1]. Only recently, a number of such proposals have been suggested. In the survey, we evaluate some of these approaches against a set of general requirements (Andersson, Martucci, & Fischer-Hübner, 2005), which assess to which degree these approaches are suitable for mobile ad hoc networks. We also discuss Sybil attacks (Douceur, 2002) in the context of anonymous communication and mobile ad hoc networks.

This chapter is structured as follows. First, an introduction to privacy, anonymity, and anonymity metrics is provided in "Background." Then, existing approaches for enabling anonymity in ad hoc networks are described in "Anonymous Communication in Mobile Ad Hoc Networks." In "Survey of Anonymous Communication Mechanisms for Ad Hoc Networks" these approaches are evaluated against the aforementioned requirements. Then, Sybil attacks in the context of anonymous communication and mobile ad hoc networks are discussed in "Future Trends." Finally, conclusions are drawn in "Conclusions."

BACKGROUND

In this section, the concepts of privacy and anonymity and their relation are introduced. Methods for quantifying anonymity are also discussed.

Definitions of Anonymity and Related Concepts

Pfitzmann and Hansen (2006) define *anonymity* as "the state of being not identifiable within a set of subjects, the *anonymity set*" (p. 6). The anonymity set includes all possible subjects in a given scenario, such as possible senders of a message.

Related to anonymity is *unlinkability*, where unlinkability of two or more items of interest (IOIs, e.g., subjects, messages, events, actions, etc.) means that within the system (comprising these and pos-

Figure 1. Unlinkability between a user in the anonymity set and an item of interest

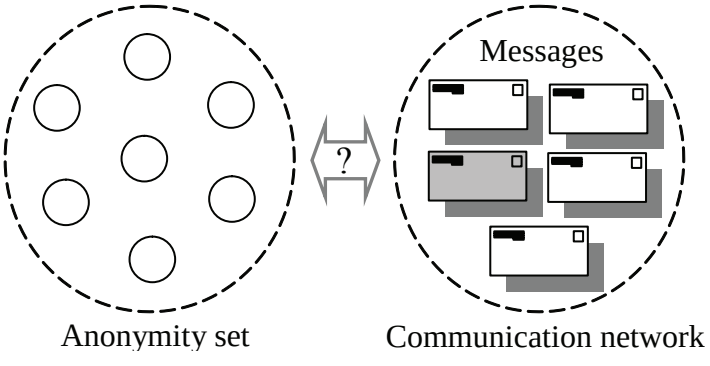
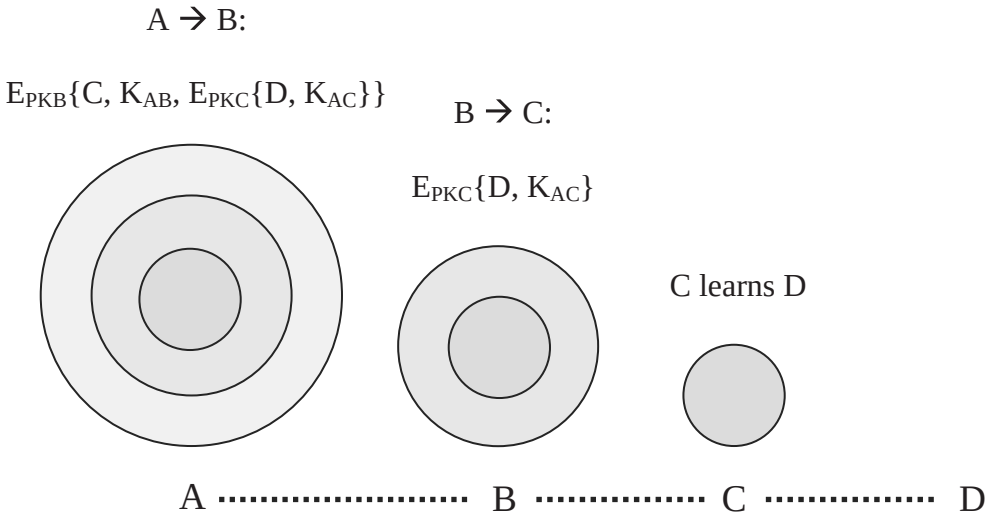


Figure 2. Setting a path between A and D (through B and C) using layered encryption; PK_B and PK_C are the public keys of B and C. K_{AB} and K_{AC} are shared symmetric keys. D is an external receiver



sibly other items), from the attacker's perspective, these items of interest are no more and no less related after his observation than they are related concerning his a-priori knowledge. (Pfitzmann & Hansen, 2006, p. 8)

Anonymity can be defined in terms of unlinkability: *sender anonymity* entails that a message cannot be linked to the sender, while *receiver anonymity* implies that a message cannot be linked to the receiver (see Figure 1).

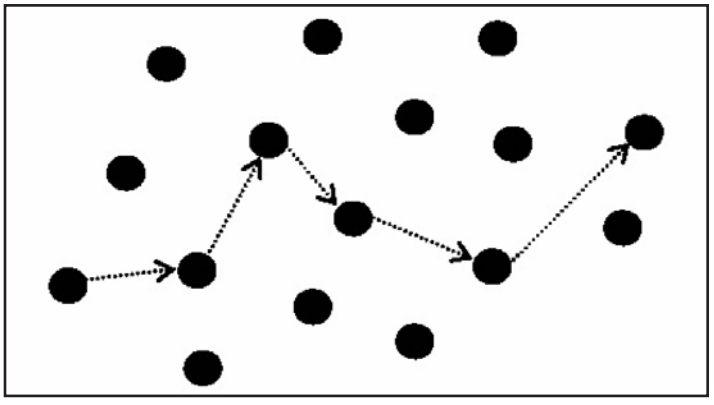
In traditional networks, such as the Internet, anonymous communication is often realized by *anonymous overlay networks*, which establish *virtual paths* consisting of one or more intermediary nodes, along which packets are transmitted. Using methods described below, the anonymous overlay network constructs the paths in such a manner that the correlation between the sender and receiver, and possibly also the identity of the sender and/or the receiver, is hidden.

A classic method enabling anonymity, where the sender determines the full path, is *layered encryption*[2]: a message is wrapped into several encryption layers. As the message propagates the network, these layers are sequentially decrypted by each successive node in the path, until the receiver decrypts the final layer. Each layer usually includes the identity of the next node in the path and a symmetric key shared with the initiating node (see Figure 2). In this way, expensive public key encryption is only used for constructing the path; for data delivery symmetric encryption is used. Messages encrypted in layers are often denoted *message onions*. Layered encryption enables anonymity as intermediary nodes do not know whether their predecessor and successor nodes are the sender or receiver, respectively.

An alternative approach, first applied in Crowds (Reiter & Rubin, 1997), is to let the sender select its successor randomly, which in turn flips a biased coin to decide whether it should end the path and connect to the receiver, or extend the path to a random node. The flipping of the biased coin is repeated until a node decides to connect to the receiver (see Figure 3). In this approach, link-to-link encryption between intermediary hops in the path is usually combined with end-to-end encryption. This approach enables sender anonymity towards network nodes and the receiver, as neither of these nodes can deduce if the previous node in the path is the sender.

Another method specifically tailored for providing receiver anonymity is *invisible implicit addressing* (Pfitzmann & Waidner, 1987). Invisible implicit addressing hides the identity of the receiver by first encrypting a message (or a part of it) with

Figure 3. "Crowds-like" path setting between the sender and receiver



the receiver's public key (or a shared symmetric key). Instead of sending the message directly to the receiver, the message is then *broadcasted* to all nodes in the network, which all must try to decrypt the message. However, only the intended receiver will be able to successfully decrypt the message.

On the Relation between Privacy and Anonymity

Privacy is recognized either explicitly or implicitly as a fundamental human right by most constitutions of democratic societies. Privacy can be defined as the right to *informational self-determination*, that is, individuals must be able to determine for themselves when, how, to what extent, and for what purpose personal information about them is communicated to others.

In Europe, the right for privacy of individuals is protected by the by a legal framework mainly consisting of the EU Data Protection Directive 95/46/EC, which defines general privacy requirements, and the E-Communications Privacy Directive 2002/58/EC, which specifically applies for personal data processing within the electronic communication sector.

An important privacy principle is *data minimization*, stating that the collection and processing of personal data should be minimized. Clearly, the less personal data are collected or processed, the less the right to informational self-determination is affected. Art. 6 (1) of the EU Data Protection Directive 95/46/EC embodies the principle of data minimization by stating that personal data should be limited to data that are adequate, relevant, and not excessive, and by requiring that data should only be kept in a form that permits identification of data subjects for no longer than it is necessary for the purpose for which the data were collected or for which they are further processed. Consequently, technical tools such as privacy-enhancing technologies should be available to contribute to the effective implementation of these requirements by providing anonymity and/or pseudonymity for the users and other concerned individuals.

More specific legal requirements for anonymization can also be found in the E-Communications Privacy Directive 2002/58/EC: Pursuant to Art.9 of the Directive: location data may only be processed when they are made anonymous, or with the consent of the user or subscriber to the extent and for the duration necessary for the provision of a value-added service.

On Measuring Anonymity

This section discusses *anonymity metrics*, which quantify the degree of anonymity in a given scenario in the following manner. First, the given attacker model, together with the properties of the anonymous communication mechanism, are passed

Table 1. A summary of anonymity metrics

Anonymity set size
A classic indicator of anonymity is the size of the anonymity set. This metric is appropriate for mechanisms in which all users are equally likely to be the sender of a particular message, as in the DC-networks (Chaum, 1988) or Crowds, regarding the Web server (Reiter & Rubin, 1997).
K-anonymity
If a mechanism provides *k*-anonymity (Sweeney, 2002), *k* constitutes a lower bound of the anonymity set size *n*. For example, $k = 3$ implies that an attacker cannot exclude more than $(n - 3)$ users from the anonymity set.
Crowds-based metric
In the Crowds-based metric[3] (Reiter & Rubin, 1997), anonymity is measured on a continuum, including the points *possible innocence* (the probability that a user is not the sender is not negligible), *probable innocence* (the probability that a user is a sender $\geq 1/2$), and *beyond suspicion* (the user is not more likely than any other user to be the sender). The analysis is based on the communication patterns in Crowds, and the result is a probability depending on the anonymity set size and the number of corrupted users.
Entropy-based metrics
In entropy-based metrics (Diaz, Seys, Claessens, & Preneel, 2002; Serjantov & Danezis, 2002), each user is first assigned with a probability of being the sender of a message. The entropy regarding which user sent the message is then calculated using Shannon's theories (Shannon, 1948). The resulting degree is system-wide and may change depending on, for example, changes in the attacker's knowledge. Diaz et al. solely bases their analysis on the probability distributions (equally distributed probabilities → max degree of anonymity), while in Serjantov and Danezis metric, a large anonymity set contribute positively to the degree of anonymity.

as input to the anonymity metric. Then, the metric determines the degree of anonymity based using for example, analysis or by simulation, depending on the metric at hand. In Table 1, we summarize the most common anonymity metrics.

Although the metrics listed above differs in many respects, the main parameters contributing to the degree of anonymity in all metrics are *size of anonymity set* (anonymity set size and *k*-anonymity), *probability distributions* (entropy-based metric by Diaz et al.), and both (entropy-based metric by Serjantov and Danezis and the Crowds-based metric).

Anonymous Communication in Mobile Ad Hoc Networks

In *proactive* routing protocols (Perkins, 2001), each node always maintains routes to all other nodes, including nodes to which no packets are being sent. Standard proactive protocols do not enable anonymity as all nodes know significant amounts of information about other nodes.

In *reactive* routing protocols (Perkins, 2001), routes between nodes are established on demand, meaning that less packets are circulated in the network, for example, for status sensing. Also standard reactive routing protocols fail to enable anonymity. As a proof of concept, consider the reactive protocols dynamic source routing (DSR) (Johnson & Maltz, 1996) and ad hoc on-demand distance vector routing (AODV) (Perkins & Royer, 1999).

- In DSR, during route discovery[4] the route request (RREQ) includes the IP addresses of the sender and receiver in plain. The IPs are also disclosed by the route reply (RREP) message. During data transfer, the path between the sender and receiver is included in plain in the packet headers.
- Also in AODV, the RREQ and RREP messages disclose the sender and receiver IP addresses. Also, routing data at each node in an active path discloses the receiver IP.

This situation applies for virtually any standard routing protocol. So far, two methods for enabling anonymous communication in mobile ad hoc networks have been proposed: *anonymous routing protocols* and *anonymous overlay networks*. They are explained in the next sections.

Anonymous Routing Protocols

An anonymous routing protocol replaces the standard routing protocol with a protocol preserving anonymity (see Figure 4). Anonymous routing protocols normally include building blocks for *anonymous neighborhood authentication*, *anonymous route discovery*, and *anonymous data transfer*. The first phase is not always included; instead many approaches assume that other mechanisms offer this service.

During anonymous neighborhood authentication, nodes establish trust relationships with their *neighbors* (i.e., nodes within one-hop distance). "Trust" implies that the nodes prove mutual possession of some valid identifiers, such as certificates, pseudonyms, public/private key-pairs, or combinations thereof.

The task of anonymous route discovery is to establish an anonymous path between the sender and receiver. Sender anonymity is often achieved through layered encryption. Sometimes, receiver anonymity is enabled by invisible implicit addressing, meaning in this context that a challenge is included in the RREQ that only the receiver can decrypt[5].

The main disadvantage with invisible implicit addressing is that all nodes receiving the RREQ must try to decrypt the challenge, resulting in considerable overhead (especially as the RREQ reaches all nodes). When the RREP is propagated back to the sender on the path created by the corresponding RREQ message, *visible implicit addressing* (Pfitzmann & Waidner, 1987) is often used to hinder nodes other than the sender from matching RREP messages with corresponding RREQ messages. This is often enabled by including sequence numbers in the RREP and RREQ so that only the sender can conclude that the sequence number of a given RREP corresponds to an earlier sent out RREQ.

During anonymous data transfer, data messages are sent along the paths created during route discovery. Only protocols that use *source routing* can apply layered encryption, as the sender in this case needs to decide the full path. Else, link-to-link encryption, possibly combined with end-to-end encryption, is normally used.

Figure 4. Anonymous routing protocol

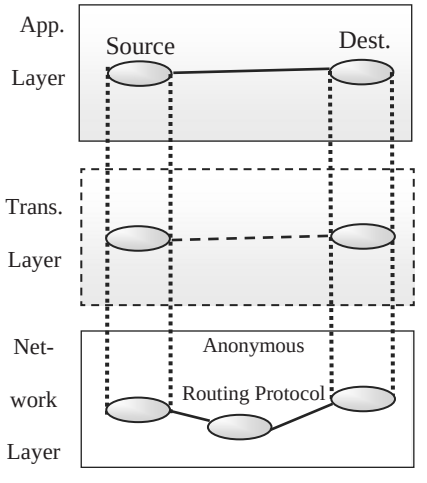
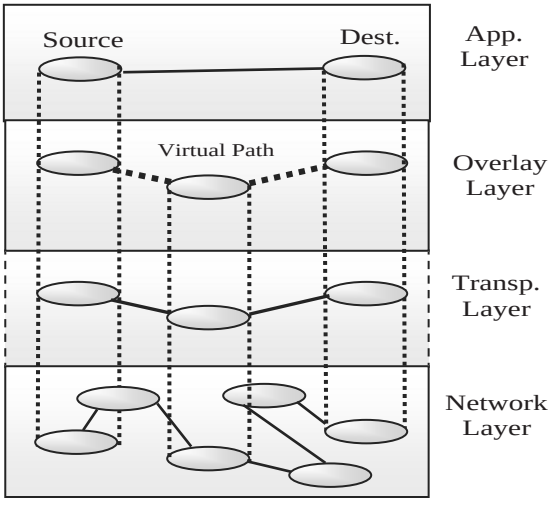


Figure 5. Anonymous overlay network



Anonymous Overlay Networks

In mobile ad hoc networks, anonymous overlay networks are normally deployed above the routing or transport layer (see Figure 5), where they can use services from the standard routing protocol (e.g., finding a route to the next node in the path) or the transport layer (e.g., reliable data delivery).

Anonymous overlay networks can be divided into the following phases: *group buildup*, *path construction*, and *data transfer.*

During group buildup, the user base of the overlay network is populated. One strategy for group buildup is to assign this task to one or more *directory servers*, where a set of nodes (or at least one node) must act as a directory server (Martucci, Andersson, & Fischer-Hübner, 2006). Similarly as in anonymous routing protocols, virtual path setting and data transfer are either based on layered encryption, or link-to-link encryption combined with end-to-end encryption.

Comparison between Anonymous Routing Protocols and Anonymous Overlay Networks

In Table 2 we summarize the respective pros and cons with anonymous routing protocols and anonymous overlay networks.

Survey of Anonymous Communication Mechanisms for Ad Hoc Networks

The survey is divided into two parts: one part for anonymous routing protocols and one for anonymous overlay networks[6]. Before the survey, however, we list the evaluation criteria against which the mechanisms included in the survey are evaluated.

Evaluation Criteria

Six requirements were defined by Andersson et al. (2005) that an anonymous overlay network should meet to be suitable for mobile ad hoc networks. These requirements are general enough to be suitable for providing the criteria against which the mechanisms surveyed in this chapter are evaluated. They are listed below:

R1. The anonymous communication mechanism must scale well. It should perform well also with a large number of participants.

R2. The anonymous communication mechanism must provide strong anonymity properties. We examine how the studied approaches resist an attacker model including a global observer[7], path insiders, other network nodes, and the receiver.

Table 2. Pros and cons with anonymous routing protocols and anonymous overlay networks

Advantages with Anonymous Routing Protocols
They make it possible to control already on the routing level what information is being disclosed during routing. Yet, this does not exclude the possibility that additional efforts may be needed in upper layers. Also, most approaches use the shortest path between the sender and receiver.
Disadvantages with Anonymous Routing Protocols
The replacement of the standard routing protocol; this will likely decrease the user base, which degrades anonymity according to many metrics. Besides, nodes may be exposed if a connection-oriented transport layer is used above the anonymous routing protocol, as they establish direct connections between nodes.
Advantages with Anonymous Overlay Networks
Flexibility; an anonymous overlay network is independent of the routing protocol and, further, compatible with applications expecting services from for example, a reliable transport layer.
Disadvantages with Anonymous Overlay Networks
The performance can be expected to be slightly worse as messages are detoured through a set of overlay nodes, instead of being transmitted on the shortest route between the sender and recipient.

R3. The anonymous communication mechanism must be fair regarding the distribution of workload among the nodes. The workload should be equally distributed (and nodes should not be forced to spend a lot of resources on behalf of others). Else, incentives should be given for accepting a higher workload.

R4. The anonymous communication mechanism must provide acceptable performance. It should be lightweight (e.g., generate few messages and avoid public key operations). We evaluate whether the studied approaches presents arguments indicating a good performance. We also evaluate whether there are strong assumptions that could hamper performance.

R5. The anonymous communication mechanism must employ a peer-to-peer paradigm (P2P) model. There should be no dependence on central hardware/services, or at least, it should be minimized. We also study whether there are some implicit requirements for centralized services that are hidden by strong assumptions.

R6. The anonymous communication mechanism must handle a dynamic topology. It must tolerate that nodes are frequently entering or leaving the network.

In the survey, we grade the approaches according to which degree they satisfy these requirements: ●●● = the requirement is satisfied to a high degree; ●● = … is satisfied to a medium degree; ● = … is satisfied to a low degree; and ○ = … is violated. Regarding the grading of R2, the approaches are graded according to which degree they provide anonymity against each item in the assumed attacker model (see R2).

Survey of Anonymous Routing Protocols

In this section, we survey a variety of prominent anonymous routing protocols proposed in recent years. The ratings of the mechanisms are listed in table-form in the next section.

Anonymous Dynamic Source Routing Protocol (AnonDSR)

AnonDSR (Song, Korba, & Yee, 2005) is a source routing protocol using invisible implicit addressing for route discovery. The RREP is created as a message onion. Both the sender and recipient know the intermediary nodes in the path. Data messages are sent as message onions on bidirectional paths. AnonDSR includes a security parameter establishment (SPE) protocol for exchanging security parameters prior to route discovery, which contains a major flaw (see R2).

R1. As the SPE protocol is used to establish shared secrets between sender and receivers, the issues regarding it (see R2) may hamper scalability.

R2. The SPE protocol broadcasts the IDs of the senders and receivers in plain. If used, AnonDSR provides merely confidentiality. If not used, AnonDSR provides sender and receiver anonymity against observers, path insiders, and network nodes.
AnonDSR changes the message appearance at intermediary hops. Yet, a global observer may correlate the RREQ sizes or trace data flows in the network.

R3. During route discovery, nodes spend energy to assess whether they are the intended receiver. Intermediary nodes must perform public key encryptions.

R4. The range of the nodes and the network size is not specified in the performance simulation of AnonDSR, and only route discovery is evaluated while data transfer
and node mobility are not considered. Also, as implicit addressing with public key
cryptography is used, AnonDSR cannot be expected to provide high performance.

R5. No special nodes needed, and thus AnonDSR adheres well to the P2P paradigm.

R6. AnonDSR does not support rebuilding of broken paths. Also, the insecurities in
the SPE protocol may cause problems for new nodes joining the network that wish to establish security parameters with existing nodes.

Secure Distributed Anonymous Routing Protocol (SDAR)

SDAR (Boukerche, El-Khatib, Xu, & Korba, 2004) is a source routing protocol enabling a system for managing trust: nodes associate their neighbors with a trust level based on past behavior. Invisible implicit addressing is used to hide the receiver identity in the RREQ. The RREP and data messages are sent as message onions.

R1. SDAR can be expected to scale badly as every node in the network must perform three public key operations per received RREQ message.

R2. SDAR offers sender and receiver anonymity against observers and other network nodes. SDAR alters messages appearance and applied padding to thwart global observers. Still, only nodes assumed to forward RREQ/RREP packets do so, others drop them.

R3. It is not specified whether the certificate authority (CA) is a central service or distributed among the nodes. When processing RREQ packets, all nodes must perform one public key encryption, one public key decryption, and one signature generation.

R4. There are serious performance issues in SDAR. For instance, every node must perform must perform three public key operations for each RREQ it forwards.

R5. The existence of a CA (or similar) is assumed for distributing public keys. It is not specified how it would be implemented.

R6. We predict that the trust management system in SDAR would suffer in a dynamic topology; it would be difficult for nodes to be highly trusted as they would be ● punished for leaving the network in the midst of a communication. Also, path rebuilding in case of broken paths is not considered.

MASK

MASK (Zhang, Liu, & Lou, 2005) does not use source routing. Prior to route discovery, MASK performs anonymous neighborhood authentication, and nodes know each other by temporal pseudonyms. For performance reasons, MASK avoids invisible implicit addressing during route discovery; instead, the receiver identity is disclosed in the RREQ. After route discovery, a sender may have multiple active paths to the receiver. End-to-end and/or link-to-link encryption is employed during data transfer, depending on the application at hand.

R1. MASK can be expected to scale well as it avoids the usage of implicit addressing. Yet, an increased node density (i.e., more neighbor nodes) may degrade performance during anonymous neighborhood authentication.

R2. MASK offer sender anonymity against path insiders, network nodes, and observers, but no receiver anonymity. MASK uses altered message appearance, random choice of paths, and per-hop message delay to harden traffic analysis during low traffic. No node forwards RREQ/RREP messages more than once.

R3 The avoidance of implicit addressing bears a positive impact on fairness.

R4. Simulation results indicate that MASK provides good performance. However, the mutual authentication between neighboring nodes was shown to be the most costly operation and in scenarios where the transmission range is small compared to the network size,
this may affect performance negatively.

R5. A trusted authority (TA) is used during the bootstrapping phase of the network.

R6. Broken paths are handled by broadcasting error packets in case of a broken path. Still, the tight synchronization scheme between neighboring nodes may lead to problems in some situations where neighboring nodes leave and join often.

Anonymous On-Demand Routing (ANODR)

ANODR (Kong, Hong, Sanadidi, & Gerla, 2005) is a source routing protocol aiming to protect privacy by avoiding persistent identifiers. Invisible implicit addressing based on symmetric encryption is used to hide the receiver identity during route discovery.

The RREP is created as a message onion. During data transfer, it is not specified whether or not the data payload is encrypted.

R1. It is unclear how senders and receivers share symmetric keys. Given that they share a key, to solve the challenge in the RREQ, the receiver
may have to try all keys shared with other nodes (see R4). Further, other network nodes must try all their shared keys to conclude that they are not the intended receiver.

R2. ANODR offers sender and receiver anonymity against observers, path insiders, and networks nodes. Senders and receivers are not mutually anonymous. ANODR uses traffic mixing to thwart observers, where messages are independently and randomly delayed. Yet, traffic patters are leaked as only nodes assumed to forward the RREP does so. Further, as the payload of data messages is not altered at intermediary hops, it is trivial for a global observer to trace data traffic.

R3. Each node must spend considerable resources when forwarding RREQ packets.

R4. There are serious performance issues in ANODR (see R1).
Although ANODR has performed reasonably well in a simulation scenario, problems can be expected in a real world scenario.

R5. No special nodes are needed, and thus ANODR adheres well to the P2P paradigm.

R6. ANODR supports path rebuilding in case of broken paths. However, it is unclear how new nodes should share symmetric keys with old nodes

Discount Anonymous On-Demand Routing (Discount ANODR)

Discount ANODR (Yang, Jakobsson, & Wetzel, 2006) is a low-latency source routing protocol that avoids invisible implicit addressing. A random time to live counter is used for RREQ/RREP messages to confuse observers (implemented by flipping a biased coin). Data are sent as message onions along unidirectional paths (i.e., a new path must be build for the reply).

R1. Discount ANODR can be expected to scale well. However, the bias of the coin flipping may have to be adapted if the geographical size of the network increases.

R2. Discount ANODR provides sender anonymity against local observers, as the coin flipping and random padding during route discovery confuse observers to a certain degree. No receiver anonymity.
Data messages are padded with random bits.

R3. There are no special nodes and no public encryption on behalf of other nodes.

R4. Discount ANODR avoids public key encryption and invisible implicating addressing.
The coin flipping may degrade performance as nodes on the shortest path may drop the RREQ, resulting in nonoptimal paths. Also, RREP packets can be lost for the same reason. Unidirectional paths also hamper performance.

R5. The nodes have to collectively administrate two values determining the bias of the coins deciding whether a node should forward a RREQ and a RREP, respectively.

R6. Discount ANODR rebuilds broken paths, but does not discuss how to collectively adapt the bias of the coin flipping when the network characteristics change.

Anonymous Routing Protocol for Mobile Ad Hoc Networks (ARM)

ARM (Seys & Preneel, 2006) aims to foil global observers by using random time-to-live values and padding for all messages. Senders and receivers share one-time pseudonyms. Invisible implicit addressing hides the receiver by including the secret pseudonym in the RREQ. The RREP is created as a message onion. Link-to-link encryption is used for data transfer.

R1. As a tight synchronization scheme is used between sender and recipients, it is assumed that senders shares keys and pseudonyms

with a limited set of receivers.

R2. ARM offers sender and receiver anonymity against networks nodes, path insiders, and observers. Senders and receivers have an a-priori relationship. In ARM, data messages have a uniform size, RREQ/RREP messages are randomly padded, and RREQ/RREP/data messages are propagated using random time-to-live values. The effectiveness of this limited dummy traffic is not formally proven.

R3. While no nodes perform public key operations, the amount of nodes forwarding RREQ/RREP and data messages increases due to the random time-to-life values.

R4. If assuming a static environment, there are no conclusive arguments orthogonal to performance. However, all nodes in ARM generate overhead traffic.
ARM has not yet been simulated to assess the performance.

R5. There are no special nodes in ARM. In a real world scenario, central infrastructure may be required to realize the assumption that each node should possess a unique identifier; it is unclear how this would clash with the P2P paradigm.

R6. The assumption that each node establishes a broadcast key with its neighbors is problematic when considering dynamic topologies. Further, ARM does not consider path rebuilding in case of broken paths.

Distributed Anonymous Secure Routing Protocol (ASRP)

ASRP (Cheng & Agrawal, 2006) is a routing protocol not based on source routing where nodes are known by dynamic random pseudonyms. Invisible implicit addressing (based on public encryption) is used for both RREQ and RREP packets. Data messages are link-to-link and end-to-end encrypted. It is not specified whether the paths are bidirectional or unidirectional.

R1. All nodes in the network must perform two public key operations per RREQ (one private key decryption and one public key generation). This hampers scalability as the more nodes in the network, the more generated RREQ packets.

R2. Senders and receivers are not mutually anonymous as they have an a-priori relationship. Anonymity is offered against path insiders and network nodes, and ASRP alters message appearance and maintains a uniform message size to confuse attackers.

R3. All nodes spend significant resources when forwarding RREQ and RREP packets. For the RREQ, see R1. For propagation of RREP packets, all nodes on the path must perform three public key operations (one private key decryption and two public key encryptions).

R4. The performance of ASRP has not been simulated. Route discovery can be expected to offer a low performance, as public key encryption is extensively used.

R5. No special nodes are needed, and thus ASRP adheres to the P2P paradigm.

R6. Path rebuilding in case of broken paths is not considered. This means that the expensive route discovery process has to be initiated for each case of path failure.

Privacy Preserving Routing (PPR)

PPR (Capkun, Hubaux, & Jakobsson, 2004) is a proactive protocol for communication between ad hoc networks interconnected by fixed access points (AP). Nodes know each other by temporal pseudonyms. In the sender network, nodes maintain the shortest path to the AP. In the receiver's network, the AP maintain the shortest paths to the nodes. Routing consists of three parts: *uplink* (distance vector protocol), *inter-station*, and *downlink* (source routing). In uplink, a sender sends a message that reaches the AP as a message onion. In downlink, the receiver's AP send an onion to the receiver.

R1. The AP and the CA are the major points of workload aggregation in PPR, but as these are centrally offered services, PPR can be expected to scale well.

R2. PPR offers sender and receiver anonymity

against observers, network nodes, and path insiders. There are no countermeasures against global observers in the senders or receivers networks, except message alteration at intermediary hops. Anonymity is quantified using the entropy-based anonymity metric (see section "On Measuring Anonymity"). There is no anonymity against the AP.

R3. Nodes do not perform special roles or execute public key operations on behalf of others.

R4. Public key encryption is only used for establishing trust relationships among neighboring nodes. The performance of PPR has not yet been simulated.

R5. PPR violates the P2P model as the existence of a CA and several AP is assumed.

R6. The existence of the AP facilitate the handling of trust and security issues in a dynamic topology. The uplink protocol is the most vulnerable part regarding routing, but it can be expected to handle dynamic topologies well.

Summary of Survey Results for Anonymous Routing Protocols

The survey results for all requirements (except R2) are summarized in Table 3. The survey results for R2 are summarized in Table 4.

SURVEY OF ANONYMOUS OVERLAY NETWORKS

In this section, we study two anonymous overlay networks for ad hoc networks: Chameleon (Martucci et al., 2006) and MRA (Jiang, Vaidya, & Zhao, 2004).

Chameleon

Chameleon can be described as a variant of Crowds adapted for mobile ad hoc networks. In Chameleon, the nodes share the responsibility of being directory servers during group buildup. Node authentication is based on certificates (the existence of a TCP (transmission control protocol)/SSL (secure

Table 3. Summary of survey results (except R2)

Requirement	*ARM*	*AnonDSR*	*ANODR*	*SDAR*	*Discount ANODR*	*ASRP*	*MASK*	*PPR*
R1: Scalability	●	●●	●	●	●●●	●●	●●	●●●
R3: Fairness	●●	●●	●	●●	●●●	●	●●●	●●
R4: Performance	●●	●	●	●	●●	●	●●	●●
R5: P2P	●●	●●●	●●●	●●	●●	●●●	●●	○
R6: Dyn. Top.	●	●	●●	●	●●	●	●●	●●●

Table 4. Summary of anonymity requirement R2

Attacker model	*ARM*	*AnonDSR*	*ANODR*	*SDAR*	*Discount ANODR*	*ASRP*	*MASK*	*PPR*[8]
Sender – observer	●●	●	●	●	●	●	●●	●
Send. – path insider	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
Sender – net. node	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
Sender – receiver	○	○	○	○	○	○	○	○
Rec. – observer	●●	●	●	●	○	●	○	●
Rec. - path insider	●●●	●●●	●●●	●●●	○	●●●	○	●●●
Rec. – net. node	●●●	●●●	●●●	●●●	○	●●●	○	●●●

socket layer) layer is assumed). Data messages are end-to-end and link-to-link encrypted or only link-to-link encrypted.

R1. The load on each node is approximately constant as the size of the network grows. However, if too few directory servers are used, this may put a limit on scalability.

R2. Chameleon offers sender anonymity against receivers and sender and receiver anonymity against local observers and malicious nodes.
The degree of anonymity is quantified by the Crowds-based metric (see "On Measuring Anonymity").

R3. A small subset of the nodes must act as directory servers. It is suggested that nodes take turns in acting as the directory servers.

R4. Chameleon is based on light-weight encryption.
However, the performance of Chameleon has not yet been assessed through simulation.

R5. Chameleon generally follows the P2P paradigm. However, nodes are assumed to possess certificates obtained in advance
and the global probability deciding the expected path length has to be administrated collectively by the nodes

R6. Chameleon repairs broken paths at the point of breach, rather that rebuilding the whole path. Without redundancy, vanishing directory servers may be a problem.

Mix Route Algorithm (MRA)

MRA applies traffic mixing[9] (Chaum, 1981) in a mobile ad hoc scenario. A subset of the nodes acts as mixes, which constitute the virtual paths. Each node assigns a mix as its *dominator mix.* A RREQ is sent to the receiver via the sender's dominator mix, triggering the receiver to register at its dominator mix with a DREG (dominator registration) message. Each mix periodically broadcasts RUPD (route update) messages containing its registered receivers and a path field, which is updated as the RUPD propagates through the network. When it reaches the sender, it contains the path to the receiver.

R1. Scalability may be hampered if the mix set is static in a growing network.

R2. As the min path length is one, a mix may learn the identity of both the sender and receiver. The first mix always learns the sender ID.
Receiver anonymity is in doubt as all mixes broadcast information in the network about which receivers it is currently providing services for (i.e., the RUPD messages).

R3. Incentives for the costly operating of mixes are left as a future research problem.

R4. MRA is based on pubic-key cryptography. Basing MRA on symmetric cryptography is left as future research. Results from a performance simulation are presented, but only different mix settings are compared.

R5. No central services are needed. Still, establishing trust between mixes and other nodes are left as future research. This may require aid from external trusted nodes.

R6. If the sender or dominator mix move, the sender may have to switch dominator mix.
If the mix set is small, problems may arise regarding the mix advertisement as nodes only retransmit advertisement messages from their dominator mixes.

Summary of Survey Results for Anonymous Overlay Networks

The results from the survey are summarized in Table 5.

DISCUSSION

From the survey, we can make the following observations:

1. **It is difficult to protect against a global eavesdropper.** None of the studied approaches implement powerful and proven countermeasures against global observers. We believe that it is an open research problem regarding how to enable such countermeasures while at the same time offering an

Table 5. Summary of survey results (left) and summary of anonymity requirement R2 (right)

Requirement	*Chameleon*	*MRA*
R1: Scalability	●●	●●
R3: Fairness	●●	●
R4: Performance	●●	●
R5: P2P	●●	●●
R6: Dyn. Top.	●●	●●

Attacker model	*Chameleon*	*MRA*
Sender – observer	●	●●
Send. – path insider	●●●	●●●/○[10]
Sender – net. node	●●●	●●●
Sender – receiver	●●●	○
Rec. – observer	●	●
Rec. - path insider	○	●/○[11]
Rec. – net. node	●●●	●

acceptable level of performance in mobile ad hoc networks[12].

2. **It is difficult to implement invisible implicit addressing efficiently.** There is a clear trade-off between on the one hand enabling receiver anonymity by using invisible implicit addressing and on the other hand satisfying the fairness, dynamic, and scalability requirements. The proposals using invisible implicit addressing either use costly public key cryptography (e.g., AnonDSR, SDAR, ASRP) or avoid public key operations at the cost of including strong assumptions regarding in beforehand mutual distribution of secrets (e.g., ARM, ANODR).
3. **It is straightforward to hide the identity of the sender from other network nodes.** This is probably because most of the approaches use classical techniques for hiding the identity of the sender, such as layered encryption, that have been used before in other contexts.
4. **No anonymous routing protocol implements sender anonymity towards the receiver.** Hiding the sender identity during route discovery would require a mechanism for hiding the propagation of the RREP messages similar (and equally costly as) to the invisible implicit addressing schemes used for hiding the propagation of the RREQ messages.

FUTURE TRENDS

A *Sybil attack* (Douceur, 2002) implies one attacker forging multiple identifiers in the network to control an unbalanced portion of the network. Sybil attacks can undermine security in, for instance, mobile ad hoc networks based on reputation schemes or threshold cryptography (Piro, Shields, & Levine, 2006). Douceur has showed that *preventing* Sybil attacks is practically impossible as it requires a TTP (trusted third party) to manually assert that each identity corresponds to only one logical entity in the network. Yet, during the years, and recently also for mobile ad hoc networks, many approaches for *detecting* Sybil attacks have been proposed. In this section, we discuss why Sybil attacks threaten anonymity in ad hoc networks, and discuss some proposed countermeasures.

The Sybil Attack in Mobile Ad Hoc Networks

Mobile ad hoc networks are highly susceptible to Sybil attacks because of, for instance, the lack of reliable network or data link identifiers, and the absence of a trusted entity capable of vouching for the one-to-one binding between physical devices and logical network identifiers. This may give the impression that ad hoc nodes are naturally anonymous as nodes could confuse observers by regularly changing their {IP, MAC} pairs. Although this may prevent long-term tracking, other problems may arise. For instance, when there is a need to identify a node offering a specific service, a rouge node could easily impersonate this service. The

absence of reliable network identifiers may also disrupt routing, as a rouge user could announce false information using multiple {IP, MAC} pairs. Also, as senders and receivers establish direct connections, they are still vulnerable to traffic analysis and physical layer oriented attacks (Capkun et al., 2004).

However, the Sybil attack also poses a threat against anonymous routing protocols and anonymous overlay networks. For both approaches, the anonymity set denotes the user base. There are some differences though. In an anonymous overlay network, the anonymity set is used as a pool of nodes serving as an input parameter to the path creation algorithm. Polluting the anonymity set with many Sybil identities might yield a path only containing Sybil identities. If this happens, the attacker can easily break anonymity by linking the sender to the receiver. In an anonymous routing protocol, however, each node only stepwise extends the path to another node within a single-hop distance, until the receiver is reached. Thus, the locations of the nodes play a more important role here, and as all Sybil identities share the same location, it is difficult for the attacker to force the creation of paths in which it controls all nodes.

Thus, the Sybil attack poses a greater threat to anonymity in anonymous overlay networks compared to anonymous routing, although it still poses a great threat to other security properties for anonymous routing.

Mechanisms for Detecting the Sybil Attack in mobile Ad Hoc Networks

In this section, we describe two recent proposals for thwarting Sybil attacks in mobile ad hoc networks.

- The fact that Sybil nodes in mobile ad hoc networks naturally travel together in clusters can be used for detecting Sybil attacks (Piro et al., 2006). Piro et al. propose a detection mechanism in which each node records all encountered {IP, MAC} pairs. If a user repeatedly observes a set of {IP, MAC} pairs sharing the same location, there is an increased likelihood that these {IP, MAC} pairs represent Sybil nodes. One drawback with this strategy is that it is unclear how to prevent a detected attacker from generating new {IP, MAC} pairs and relaunch a new attack later, as there is no underlying long-term identity that can be blocked from the system.
- Another strategy is to cryptographically guarantee a one-to-one mapping between all temporal network identifiers seen in a particular network and corresponding certified long-term identifiers (Martucci et al., 2008). To tailor this approach for ad hoc networks, the nodes must be able to assert the validity of the temporal identifiers without having to interact with the TTP. Further, to protect privacy, only the TTP should be able to link a temporal identifier to the corresponding long-term identifier and there should be unlinkability between temporal identifiers used in different contexts. The fact that you need reliable identifiers to protect against the Sybil attack and to provide reliable anonymous communication has been labeled as the *identity-anonymity paradox* (Martucci et al., 2006).

CONCLUSION

In mobile ad hoc networks, anonymous communication can either be enabled by anonymous routing protocols or anonymous overlay networks. Currently, anonymous routing is the most popular approach, although future requirements, such as flexibility regarding the applications, may raise the need for anonymous overlay networks.

We evaluated commonly proposed anonymous routing protocols and anonymous overlay networks for mobile ad hoc networks against a set of evaluation criteria and showed that a number of research challenges remain. For instance, it is difficult to offer receiver anonymity without using a complex and performance-hampering invisible implicit addressing scheme, and it is further difficult to protect against global observers.

Finally, we introduced Sybil attacks, a notorious

threat to all computer networks, including mobile ad hoc networks. We expect that the area of enabling reliable identifiers in a privacy-friendly manner is an interesting future research area.

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KEY TERMS

Anonymity: The state of being not identifiable within a set of subjects.

Anonymity Metrics: Metrics for quantifying the degree of anonymity in a scenario.

Mobile Ad Hoc Network: Networks constituted of mobile devise which may function without the help of central infrastructure or services.

Privacy: The right to informational self-determination, that is, individuals must be able to determine for themselves when, how, to what extent, and for what purpose personal information about them is communicated to others.

Receiver Anonymity: Implies that a message cannot be linked to the receiver.

Sender Anonymity: Means that a message cannot be linked to the sender.

Unlinkability: If two items are unlinkable, they are no more or less related after an attacker's observation than they are related concerning the attacker's a-priori knowledge.

END NOTES

1 As devices in ad hoc networks are responsible for their own services, including security and routing, protocols for anonymous communication for wired networks are not suitable for ad hoc networks, not even those based on the

peer-to-peer paradigm (P2P) (Andersson et al., 2005).

[2] This method is sometimes also called telescope encryption. A public key based version of the method was initially introduced by Chaum (1981). Onion Routing, which only uses public key encryption for setting the path, and then relies on symmetric encryption, was later proposed by Goldschlag, Reed, and Syverson (1996).

[3] The Crowds-based metric was developed for Crowds, but has since been used in other contexts.

[4] This denotes the process of setting a path between the sender and a receiver. First, the sender floods a route request (RREQ) into the network, which triggers the sending of a route reply (RREP) from the receiver to the sender. During the propagation of the RREQ and RREP, respectively, the path is interactively formed.

[5] In the context of mobile ad hoc networks, this method is often referred to as a global trapdoor.

[6] In the survey, we omit approaches relying on the existence of either a positioning device (e.g., GPS) in the mobile devices or a location server in the mobile ad hoc network.

[7] A global observer is an observer that is capable of observing all networks traffic in the whole network.

[8] Note that no anonymity is provided against the access points (not included in attacker model).

[9] Batching and reordering traffic to hide the correlation between incoming and outgoing traffic.

[10] No sender anonymity if path length is one.

[11] No receiver anonymity against last mix on the path.

[12] It is commonly believed that omnipresent protection against a global observer can only be achieved if all nodes transmit a constant flow of traffic, requiring massive usage of dummy traffic.

Chapter XXVIII
Secure Routing with Reputation in MANET

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ABSTRACT

The pervasiveness of wireless communication recently gave mobile ad hoc networks (MANET) significant researchers' attention, due to its innate capabilities of instant communication in many time and mission critical applications. However, its natural advantages of networking in civilian and military environments make it vulnerable to security threats. Support for anonymity in MANET is orthogonal to a critical security challenge we faced in this chapter. We propose a new anonymous authentication protocol for mobile ad hoc networks enhanced with a distributed reputation system. The main objective is to provide mechanisms concealing a real identity of communicating nodes with an ability of resistance to known attacks. The distributed reputation system is incorporated for a trust management and malicious behaviour detection in the network.

INTRODUCTION

The contemporary information society extensively takes advantage of wireless communication using several specific network technologies. This continuously evolving area provides a flexible and convenient way for improving work standards in business, home, education, or rescue applications. Thanks to the pervasiveness of private unlicensed spectrum technologies such as Bluetooth and IEEE 802.11 family protocols, the communication between personal and handheld electronic devices is easier, comfortable, and mobile. Through the years, a lot of researches' efforts were devoted to the functional and network performance improvements, covering existing standards designed for fully cooperative environments. However, many first pioneering deployments of wireless networks quickly turned out its several vulnerabilities they suffer from. Since that time substantially more

attention has been paid to the security as a supplementary service protecting and supporting performance in wireless communication. The specific and unique characteristics of mobile ad hoc networks (MANET) such as a multihop routing and highly dynamic topology impose a new type of security concerns that we present in this chapter.

In response to the vulnerabilities being identified in several MANET protocols a set of security considerations have taken place in a number of extensions to existing nonsecure approaches. Even though, the strong security requirements are met in many MANET protocol designs, only few of them address anonymity and privacy guaranties (Boukerche, 2004; Ciszkowski & Kotulski, 2006; Kong & Hong, 2003; Zhang, Liu, & Lou, 2005), which are treated as an orthogonal to security critical challenge we discuss in this chapter. On the example of a novel anonymous authentication protocol (ANAP) for mobile ad hoc networks (Ciszkowski & Kotulski, 2006) we present an enhanced distributed reputation system designed for efficient and secure routing in MANET. The main objective of this work is to provide protocol with mechanisms concealing the real identity of the communicating nodes maintaining the resistance to known attacks (Chaum, 1981; Pfitzmann & Hansen, 2005). The distributed reputation system is incorporated in order to build and manage mutual trust of the communicating nodes. The trust knowledge reflects a trustworthy and malicious activity in the network, effectively improving secure routing in MANET by means of anonymous authentication and path discovery phases. ANAP delivers links for secure exchange of data, taking advantage of an on-demand routing approach (Hu et al., 2002; Perkins & Royer, 1999; Royer & Toh, 1999).

The following sections present related work and protocol designs focusing on the distributed reputation system improving secure and anonymous routing in MANET. Two last sections cover some concluding remarks and further research directions.

BACKGROUND

MANET is a set of mobile nodes which operates wirelessly in an environment with a devoid of fixed network structure enforced by self-configuring and self-organizing mechanisms. All its nodes are free to move, join, or leave the network in ad hoc manner, while the end-to-end communication between nodes being beyond its radio range is performed in a multihop fashion. This specific feature demands for additional requirements to every node that, apart from sending and receiving data, must act as an interconnecting router. Since every node may be obliged to perform data forwarding, appropriate routing algorithms were developed to meet such a requirement. The main objective of routing protocols for ad hoc network is creating an up-to-date multihop communication path in a dynamically changing network topology. The appropriate and specific path discovery and path maintenance algorithms have already been developed which characterizes particular routing protocols. One can distinguish two groups of protocols designed for MANET: reactive (on-demand) and proactive (table-driven). The first type tries to resolve a path to a destination node on the source node demand, whereas the second approach is more preventive and continuously keeps routing tables up to date by monitoring the nearest neighbourhood. The detailed description and comparison of both classes of routing protocols for ad hoc networks may be found in works by Hu et al. (2002), Johnson (1994), and Royer et al. (1999).

At the moment several applications apart from strict MANET paradigm take advantage of the dynamic ad hoc routing phenomenon and make use of it in an akin to MANET wireless environments such as wireless mesh networks or vehicular ad hoc networks (VANET). This increasing application potential gives the MANET's security a primary concern for researching communities.

For MANETs there are several solutions considering multilayer defence against known attacks, mainly focusing on provided services such as authentication, anonymity, confidentiality, and integrity based on the network layer security. Most of them extend existing protocols for which the

scope of security considerations was significantly limited, such as AODV, DSR, DSDV, and LSP (Royer et al., 1999). A complete protection from various attacks in MANET takes into account actions such as prevention, detection, and reaction. The prevention is usually achieved by means of secure routing protocols (path discovery and maintenance), while the abnormal behaviour detection is performed by monitoring end-to-end communication or by overhearing the local neighbourhood. In both cases the security extensively employs different cryptographic primitives authenticating routing messages (Hu & Perrig, 2004; Yang, Luo, Ye, Lu, & Zhang, 2004). The main difference between authentication schemes was characterized in the following list:

- First method takes advantage of a single shared session key widely distributed in the group of MANET nodes, for example, used in secure routing protocol (SRP) (Papadimitratos & Haas, 2002). This approach does not provide anonymity and is vulnerable to single node compromise.
- Second method assumes sharing pair-wise keys between all nodes in the networks and is used for HMAC in Ariadne (Hu et al., 2002). It suffers from lack of scalability and in this case of N nodes; N(N-1)/2 keys are required priory to allow communication.
- Third approach makes use of scalable public key cryptography where digital certificates and signatures allow the mobile nodes to be mutually authenticated (Sanzgiri, Dahill, Levine, Shields, & Belding-Royer, 2002; Zapata & Asokan, 2002). It is a principle method for secure routing in ARAN, SEAD, and SAODV. Although this method is linearly scalable when a node's number increases, its flexibility and efficiency may suffer from vulnerability to denial-of-service (DoS) attacks and computation overhead.

All of aforementioned methods assume existence of trusted authority TA (certifying authority CA) dealing with a key setup phase. The online and distributed TA supports key management and should assure a self-configurable principle of MANET, which is an important and challenging task for the nowadays research (Hu & Perrig, 2004; Mangipudi, Katti, & Fu, 2006; Yang et al., 2004).

Even though the many solutions for mobile ad hoc networks ensure secure communications (Hu & Perrig, 2004; Yang et al., 2004), very few of them address privacy guaranties as complementary to a strict security approach (Kong, Hong, & Gerla, 2005). The main objective of the anonymous communication in mobile ad hoc network is to provide privacy for all of its users represented by the nodes. Demanding for anonymity imposes a series of requirements for protocol construction and creates the new types of attacks. A set of formal notions of the anonymity and its related properties can be found by Chaum (1981) and Pfitzmann and Hansen (2005), where the authors characterize a general anonymous system with identity management designed for fixed network topology but easily applicable for MANET. ANODR protocol (Kong & Hong, 2003) delivers a full irrevocable anonymity based on symmetric cryptography primitives. Note that the pure anonymity of the users limits the accountability for malicious activity in the network. In order to avoid such a restriction a revocable anonymity was introduced which is based on pseudonyms managed by trusted third party, as it was proposed in ANAP (Ciszkowski & Kotulski, 2006), MASK (Zhang et al., 2005), and SDAR (Boukerche, 2004). Authors of SDAR identified that anonymous MANET is an environment suffering from the lack of personal and direct incentives to be well cooperative between nodes. In order to overcome this important vulnerability, SDAR was proposed: a node's trust management system providing a scoring of node's local activity whereby during the communication the most trustful nodes were promoted.

In the anonymous communication in the mobile ad hoc networks the trust management is used for misbehaviour detection and nodes evaluation. This evaluation creates a long-term node assessment called a reputation. A reputation is known from e-market mostly thanks to online auctioning systems, but in terms of MANET, it was defined by

Buchegger (2005) as a means for providing incentives for good behaviour of nodes and metric used for identifying the most truthful node. The main purpose of reputation management is a detection of any untrustworthy behaviour in the network interfering to ordinary and regular functions such as routing (next hop finding), forwarding (packets relaying), and, finally, isolating originators of such an activity. This goal of reputation management motivates nodes to be cooperative and improves the network security and performance.

Blaze, Feigenbaum, and Lacy (1996) argue for enhancing the existing trust management systems that incorporate PGP (Zimmermann, 1994) and PKI infrastructure of X.509. They propose a flexible and independent security system, PolicyMaker, which deals with policy management. They point out that trust transitiveness usually depends on the context of service, for example, e-main, link capacity, and quality of service in data forwarding, while PGP and X.509 support a trust transiting considering only guaranties of an association of public key with its owner's identity. One of the first solutions addressing the trust transitiveness in MANETs was protocol's Confidant (Buchegger & Le Boudec, 2002) and SDAR. Confidant incorporates the reputation system maintaining a node trust, path rates, and shared reputation information; however its construction does not provide the anonymous communication. The protocol SDAR supports a secure and anonymous communication but the proposed reputation system is limited in its efficiency because it supports only three levels of permissible trust that a node may obtain.

In the next section we present an introduction to the reputation-based secure routing, defining concepts of trust and reputation in relation to the mechanism of its modelling and managing. In the main part of the following section, we introduce an example of a distributed reputation model implemented in an anonymously authentication protocol for mobile ad hoc network (Ciszkowski & Kotulski, 2006).

REPUTATION-BASED SECURE ROUTING IN MANET

In many secure routing protocols for mobile ad hoc networks (Hu & Perrig, 2004; Yang et al., 2004) it can be found only few proposals considering anonymity as critical service assuring privacy for MANET's customers ANODR, MASK, SDAR and ANAP. The demand for anonymity in an open environment, such as mobile ad hoc networks, decreases node accountability and may be a source of unexpected behaviour coming from unknown network identities. It is postulated that by incorporating a distributed reputation system into secure routing protocol we can detect and avoid cooperation of hostile and anonymous nodes. The reputation system is an essential part of routing in MANET, which facilitates a prediction of node's behaviour and improves a performance of an anonymous communication. The reputation system provides a set of mechanisms and polices that when applied locally, similar to PolicyMaker (Blaze et al., 1996), allow assigning of a value of trust to a particular action performed in the network. Such an approach maintains trust knowledge of local neighbourhood activity without revealing its real identity. This information acts as a probability of future intentions and behaviours in the network and may be used to enforce the path discovery process by choosing the communication path containing only trusted nodes.

Trust and Reputation Modelling

In the literature it can be found that many interchangeable cases of the use of reputation and trust, even though, in popular understanding, they are not synonyms. In order to avoid any mistakes in this chapter we correspond with Hussain, Chang, and Dillon's (2004) definitions, and by trust we mean a subjective probability of a one peer (trustee), so that the particular actions of another peer (trusted) they are willing and capable to perform will be done according to the trustee's expectations in the given context and time. The defined trust is asymmetrical and usually represented by knowledge gathered during direct interactions and observations. The

reputation is a perceived grade of trustworthiness to a particular peer created by their historical behaviour during observations and interactions with third party peers in the given context and time. This definition describes a concept of the peer's reputation expressed by a level of aggregated trust exchanged and shared between other peers. The main difference between the reputation and trust is that the subjective trust is usually created by the direct and own experience while the reputation is established combining other's trust knowledge. Considering the stated explanation, the reputation tends to represent a generalized opinion in a local group of peers. As the reputation may comprise an aggregated trust of several network nodes, it becomes a very valuable metric that supports the routing process. The measure expressing the level of trustworthiness for a particular node is also an important incentive for cooperation and good behaviour in the anonymous ad hoc network.

In terms of trust aggregation, sharing, and assessment, we can distinguish several types of modelling and management of the reputation in collaborative environments such as P2P networks, auctioning systems, and in particular, MANET. In one of the leading concepts of modelling, the distributed reputation assumes probabilistic representation of trust and introduces importance or uncertainty of shared knowledge. Lee, Hwang, Lee, and Kim (2006) apply the fuzzy set theory for the trust modelling. This approach defines multiple evaluating criteria with different importance factors. It allows building of trust by classifying the different types of observations and aggregating them with different importance weights. Since every criterion is strictly related to a class of observations, the interpretation of shared reputation depends on own preferences. Jøsang (2002) introduces the subjective logic where the trust is represented by a probability vector named an opinion, which is composed of belief, disbelief, uncertainty, and atomicity function. The atomicity function additionally determines the rate of the uncertainty in expected value of trust. Based on this approach, Huang, Hu, and Wang, (2006) propose a system similar to Lee et al.'s (2006) weighted evaluation trust, but the weights are dynamically modified by a feedback control unit according to the trust-policing module. The related probabilistic trust management methods are very attractive, but they usually suffer from complexity of probability logic incorporated into calculations.

Very interesting and especially suitable for MANET trust model is an enhanced reputation model for mobile ad hoc networks proposed by Liu and Issarny (2004). It takes advantage of the monitoring system as a principle module of misbehaviour detection (Buchegger & Le Boudec, 2002), which was effectively improved by exchanging the second-hand information (Buchegger, 2005). This work considers self-experience of nodes, time, and context dependency and introduces the definitions of services and recommendation reputation. In SDAR for anonymous MANET a three level of community management trust was introduced, in which every node may act as a central node of the community consisting of the rest nearest one-hop neighbours. The reputation is created locally, based on detected packet drops and modifications. In the network one distinguishes three classes of trust, which are assigned to every node. Trustworthy behaviour usually promotes nodes to the higher trust level but finally it may depend on local polices. A route discovery process is conducted considering a node's class membership. The main drawback of this approach is a low granularity of trust classes and considering only the local own experience.

Distributed Reputation for Secure MANET

In this section we present a distributed reputation system, which extends Liu's and Issarny (2004) reputation model incorporated in ANAP (Ciszkowski & Kotulski, 2006). We propose a new method of evaluating recommendation reputation considering past experience and recommendation reputation of voters (recommends). We define two types of second-hand information, related to the immediate nodes and cumulative reputation describing aggregated reputation of immediate nodes' neighbourhood. Second-hand information is exchanged on demand of interested nodes. In order to detect malicious activity and any anomalies in

information exchange we incorporated a second-hand recommendation validation by a statistical correlation approach.

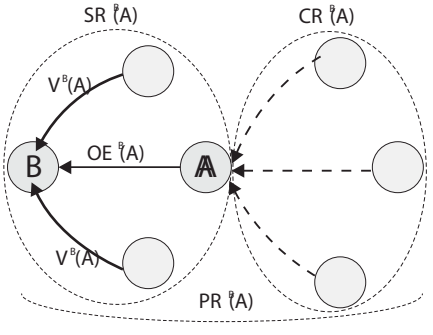
The reputation depends on time, own past experience, second-hand information, and is expressed by a level of trust. These input features are organized with a reputation dynamic evaluation scheme providing a node assessment. A proposed model consists of the following definitions and assumptions:

- $\mathbf{SR_n^B(A)}$ – service reputation held by **B** expressing a level of trust to node **A** in time **n**, and is taken into account whenever **B** is going to interact with **A**
- $\mathbf{IR_n^B(C)}$ – information reputation held by **B** expressing the level of trust for second-hand information $\mathbf{V_n^{BC}}$ received from node **C** at time **n**, and is used for evaluating received the second-hand information from **C**
- $\mathbf{V_n^{BC}(A)}$ – second-hand information (vote) coming from **C** to **B**; contains a recommendation of trust to node **A**, for an honest node is equal $\mathbf{SR_n^C(A)}$
- $\mathbf{CR_n^B(A)}$ – cumulative reputation expressing an aggregated grade for **A**'s neighbourhood which is unreachable by **B** at time **n**, it acts as a reputation of path going from **B** through node **A**
- $\mathbf{PR_n^B(A)}$ – path reputation is a product of service and cumulative reputation and expresses the trust of a path going from node **B** through the node **A** at time **n**,
- $\mathbf{STE^B(A)}$ – satisfaction degree of node **B** during elementary interaction with the node **A**
- $\mathbf{ST_n^B(A)}$ – average satisfaction degree of node **B** during several elementary interactions with the node **A** in time **n**
- $\mathbf{OE_n^B(A)^t}$ – own experience of node **B** based on history of interactions with the node **A**
- Nodes exchange **V** information with truthful neighbours
- Aforementioned parameters vary in range <-1,1>, where the most positive value reflects to the trustworthiest parameter

The building process of key reputation metrics is illustrated in Figure 1.

We introduced a virtual discrete time **n** in order to make the event-based nature of building reputation independent on real time. The virtual time depends on a number of events and its quantum consists of constant **Q** elementary interactions $\mathbf{STE_i}$. Every $\mathbf{STE_i}$ is expressed by Equation (1) and

Figure 1. Model of distributed reputation system providing the following vector metrics: own experience OEB(A), votes VB(A), service reputation SRB(A), cumulative reputation CRB(A) and path reputation PRB(A)



depends on a set of weighted metrics **m** monitored by a node during network packets exchanging. A metrics vector corresponds to all kinds of detectable observations such as every overheard packet modifications, attacks (DoS, reply attack, etc.), and network quality of service (QoS) parameters, for example, transmission delay and packet drops. This set of direct measurement is evaluated by expectation function **E**, which allows the assigning of different importance factor to a particular type of its arguments. The $\mathbf{STE_i}$ building process should take into account all observable misbehaviour defined at the end of this section.

$$STE_i^B(A) = \sum_{j=0}^{L-1} w_j E_i(m_j) \tag{1}$$

After every **Q** interactions between **B** and **A**, the time value **n** is incremented and aggregated $\mathbf{STE_i}$ updates satisfaction degree **ST**:

$$ST_n^B(A) = \frac{1}{Q}\sum_{i=0}^{L-1} STE_i \tag{2}$$

The proposed model takes advantage of past experience with a finite **L**-length memory, where every reputation measure with time **n - L** becomes the oldest value and is forgotten.

An own experience of node **B** at time n is based on the history of interactions with the node **A** and is evaluated as weighted average of **ST**:

$$OE_n^B(A) = \frac{\sum_{j=0}^{L-1} \gamma_j ST_{n-j}^B(A)}{\sum_{j=0}^{L-1} \gamma_j},$$

where

$$\gamma_n = \begin{cases} \rho, & n = 0 \\ (1-\rho)^{n+1}, & n > 0 \end{cases} \tag{3}$$

γ_n is an exponential fading function and depends on time, where $0<\rho<1$.

Whenever the own experience (**OE**) is updated or the second-hand information **V** is obtained the service reputation (**SR**) is modified. **SR** consists of own experience and weighted average of votes taking into account the information reputation (**IR**) of recommending nodes. Considering a set **GV** of voting nodes on **A**, the node **B** takes into account only nodes with positive **IR**. Own information is usually more valuable (Kong et al., 2005; Buchegger, 2005), hence scaling factor $\alpha \in <0,1>$ is introduced to the formula:

$$SR_n^B(A) = \alpha OE_n^B(A) + (1-\alpha)\frac{\sum_{p\in GV\setminus B} IR_n^B(p) V_n^{Bp}(A)}{\sum_{p\in GV\setminus B} IR_n^B(p)}, \qquad IR_n(p) > 0 \tag{4}$$

Note that nodes cooperating rarely have small service reputation **SR** and are less trustworthy.

In order to evaluate a credibility of recommendation **V** obtained from neighbouring nodes, it is required to update the information reputation (**IR**). In our model we propose a formula, which considers close relations between node's experiences (**OE**) with particular node, say **A**, as well as other voter's **IR**:

$$IR_n^B(C) = \beta OE_n^B(C) - \frac{\sum_{p\in GV\setminus B} IR_n^b(p) \,|\, V_n^{Bp}(C) - OE_n^B(C)|}{2\sum_{p\in GV\setminus B} IR_n^B(p)}, \quad IR_n(p) > 0 \tag{5}$$

where $\beta \in <0,1>$ is a scaling factor for own experience. It is recommended to let the service reputation (**SR**) evolve more dynamically then an information reputation (**IR**), which is equivalent to $\beta < \alpha$. This allows nodes to rehabilitate their service reputation faster than their recommendation credibility. It means the nodes providing only a good service are able to rebuild already lost the information reputation.

Revealing all node identities on the communication path one could provide an easy way for building a global node reputation and evaluate a reputation along path, from the source to the destination. However, in ANAP for a communication path longer than three hops a physical identity of nodes lasts pure anonymous. Therefore we evaluate a cumulative reputation (**CR**) for the intermediate node, as an aggregated trust for its neighbour nodes, which are unreachable by the source node. This metric reflects a reputation along a path and does not break the anonymity:

$$CR_n^B(A) = \frac{\sum_{p \in GAV \setminus GBV} V_n^{Bp}(A)}{|GAV \setminus GAB|}, \qquad IR_n(p) > 0 \tag{6}$$

where **GBV** and **GAV** are sets of nodes being in neighbourhood of respectively node **B** and **A.**

Every time a source node wants to send data to an immediate node it calculates a path reputation (**PR**) as a product of service reputation, combining own and immediate nodes experience and cumulative reputation:

$$PR_n^B(A) = SR_n^B(A) CR_n^B(A) \tag{7}$$

A set of path with the highest **PR** is selected for communication. For path, which **PR** falls below zero, a communication channel should be closed.

A trust history evolution of own and immediate nodes is stored at every node in appropriate reputation parameters, represented by **L**-length vectors. This set of information is used for validating incoming second-hand votes by means of correlation analysis. Note, the own experience vector **OE** is a weighed moving average process (**MA**) of the order **L**. The **γ** function coefficients determine the dynamic of changes in **MA** process and make the all observation jointly dependent. As it was defined in Equations 4 and 5 the correlation is propagated to the service reputation (**SR**) and information reputation (**IR**) (indirectly by **IR** influence to **CR** and **PR**).

The correlation validation is based on autocorrelation functions of own experience $\hat{R}_n^V$ second-hand information $\hat{R}_n^O$ and distance functions, respectively **O** and **V**:

$$D_O = \sum_{i=0}^{L-1} (\hat{R}_i^O - \hat{R}_{i+1}^V)^2 \tag{8}$$

$$D_V = \sum_{i=0}^{L-1} (\hat{R}_i^V - \hat{R}_{i+1}^V)^2 \tag{9}$$

where $\hat{R}_n^O$ and $\hat{R}_n^V$ are estimators of autocorrelation function know as a convolution time series evaluated for a linear and stationary system, such as a reputation system:

$$\hat{R}_i^O = \sum_{n=0}^{L-1} OE_n OE_{n-i} \tag{10}$$

$$\hat{R}_i^V = \sum_{n=0}^{L-1} V_n V_{n-i} \tag{11}$$

Defined distance functions for every new vote **V** provide a measure of correlation change between own experience and already known history of votes from a particular node. Any attempt of voting unrelated to the historical observation will be observed by substantial increase of distance function $\mathbf{D_V}$. Additionally we can observe how much our own experience differ from the received by neighbour nodes analyzing value of $\mathbf{D_O}$. These two metrics should be taken into account if their values exceed some threshold separately defined for each of them $\mathbf{Th_O}$, $\mathbf{Th_V}$. In the case where the abnormal behaviour is detected following actions may be undertaken:

- $\mathbf{D_O} > \mathbf{Th_O}$ and $\mathbf{D_V} > \mathbf{Th_V}$ - the votes from misbehaved nodes are rejected and their information reputation is arbitrary decreased.
- $\mathbf{D_O} < \mathbf{Th_O}$ and $\mathbf{D_V} > \mathbf{Th_V}$ - the votes are accepted but service reputation (SR) is updated with higher scaling factor a. This less restrictive approach gives an ability to react to dynamically changing reputation but prevents too fast malicious attacks from targeting too discrediting nodes.
- $\mathbf{D_O} > \mathbf{Th_O}$ and $\mathbf{D_V} < \mathbf{Th_V}$ - in this case a node reaction should be similar to the previous anomaly, however, it may be symptomatic of long term attack against reputation service by nodes being in collusion.

Every node during messages exchanging collects its own experience of elementary interactions **STE**. The following list describes types of behaviour that can be taken into consideration during reputation building:

- **Forwarding:** During network operations nodes are able to verify integrity of messages anonymously forwarded in behalf of them by overhearing the first intermediate node. Every message tampering, delays, double

relays, and dropping are detected as a malicious behaviour.

- **Receiving:** Every obtained message that could not be successfully verified, repeated messages and break down paths without error message notification coming form involved immediate node should be treated as untrustworthy.
- **Anonymous path establishing:** In case of ANAP, an anonymous path establishing a three-pass process and in every phase multilayered operations are performed. By default every request packet **REQ** should be forwarder only once by every node. In the case of detection of behaviour inconsistent with this rules or obtaining multiple copies of reply **REP** or error **ERR** messages, the reputation system should be informed.
- **Recommendation exchanging:** Sharing a reputation between nodes allows to compare an own experience with a given by recommending nodes. In the case when the one of the votes differs much from the rest voters there exists presumption of node discrediting. Additional statistical cross-validation (Hildebrand, Laing, & Rosenthal, 1977) methods may be used for this case evaluation.

The interaction of the presented reputation system with the anonymous authentication protocol is performed ensuring the purely anonymous communication. The reputation information is exchanged between nodes in on-demand manner of interested node, encrypted by public key of message originator. This ensures that recommendation sharing is hidden and may be read only by legitimated recipients.

FUTURE TRENDS

In the contemporary information society the mobile ad hoc networks is a promising and very attractive alternative for wireless access networks. Proposed in the last section, a solution for managing routing in secure MANETs is based on the distributed reputation system. We expect in the near future a class of new attacks will appear focusing on the reputation system. Keeping in mind that the security of the every system depends on its weakest point, the potential vulnerabilities of the reputation system may be treated as an important challenge for the future research. Two interesting forms of attacks for the reputation system may be Sybil and Collusion attack. In the case of first, the attacker takes advantage of using multiple identities by adversary's node, while in the second several malicious nodes are in collusion. In both cases it is highly possible that own experience and shared reputation may be affected by these attacks. Proposed by us, autocorrelation analysis for anomaly detection in reputation recommendations may not be sufficiently sensitive to cope with mentioned attacks. Now, a statistical method validation of recommendation, such as the cross-validation (Hildebrand et al., 1977), has been proposed and is being developed. It is a very promising direction of research, since the cross-validation is very flexible and easily applicable for complex data. On the other hand, the method is mathematically rigorous, so the obtained results are verifiable and easy to implement.

Another interesting area is the secure routing in MANET enforced by an ontology-based reputation system (Caballero, Botia, & Gomez-Skarmeta, 2006). A conceptual-based reputation may be identified as a reputation created for different types of services provided in MANET with an ability of creating a similarity measures between them. This approach in a natural way improves the model of incentives for the ad hoc communication giving ability to treat MANET networks as a service oriented.

At the moment several applications apart from strict MANET paradigm take advantage of the dynamic ad hoc routing phenomenon and make use of it in an akin to MANET wireless environments such as wireless mesh networks or vehicular ad hoc networks (VANET). This example shows that researching in the MANET's area may bear unlimited applications.

CONCLUDING REMARKS

In this chapter we presented a new approach of distributed reputation-based secure routing mechanism in MANET. In the background section the main concepts of secure and anonymous mobile ad hoc networks were presented. The overview of applied authentication schemes in secure MANET was analyzed giving an introduction to trust management and reputation basis as a mean for detecting misbehaviour and improving the routing performance.

In the main part of this chapter we focused on a new proposal of a distributed reputation system, which was an extension of the Liu and Issarny (2004) model and which was introduced in the anonymous authentication protocol for mobile ad hoc networks (Ciszkowski & Kotulski, 2006). We emphasized in the proposal the method of evaluating recommendation reputation considering the past experience and recommendation reputation of voters. We defined two types of the second-hand information, related to the immediate nodes and cumulative reputation, describing aggregated reputation of immediate nodes' neighbourhood. Second-hand information is exchanged on demand of interested nodes. In order to detect the malicious activity and any anomalies in the information exchange we incorporated the second-hand recommendation validation by the statistical correlation approach.

We pointed out the the security in MANET is a primary concern for researchers, in particular this becomes a very important issue since several applications apart from strict MANET communication model take advantage of the dynamic ad hoc routing phenomenon.

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KEY TERMS

Anonymity: Aims at hiding an entity's identity completely.

Anonymous Authentication: A method of proving that someone has rights to certain actions or resources without disclosing the user's real identity.

Attacks: Attacks on MANET can destroy availability of nodes (attacks on routing) and contest reputation of nodes.

Authentication: A method of proving someone's identity, especially if that someone is an authorized user of processes or resources.

Collusion Attack: If a number of adversary nodes make a coalition against reputation of other nodes.

Cross-validation: A statistical method derived from cross-classification which main objective is to detect the outlying point in a population set. It is a candidate method for anomalies detection in the reputation sharing (recommendations) and regular communication in MANET. **Denial-of-Service (DoS) attack:** An attempt of keeping an access to computer resources (nodes) unavailable, especially by generating dummy traffic from one source (**DoS**) or a large number of sources (**distributed DoS [DDoS]**).

MANET: Mobile ad hoc network is a self-configuring network of freely moving nodes connected by wireless links that can constitute a path joining two arbitrary nodes of the network.

Privacy: The ability of keeping secret someone's identity, resources, or actions. It is realized by anonymity and pseudonymity.

Pseudonymity: Hides the user's real identity behind some virtual identity called a pseudonym.

Reputation: Perceived grade of trustworthiness to a particular peer created by their historical behaviour during observations and interactions with third party peers in the given context and time

Routing: A method of selecting a path (a chain of links between neighbouring nodes) from a source node to a destination node. One can distinguish two groups of protocols designed for MANET: reactive (on-demand) and proactive (table-driven). The first type tries to resolve a path to a destination node on the source node demand, whereas the second approach is more preventive and continuously keeps routing tables up to date by monitoring the nearest neighbourhood.

Security: Security of a system means that the system does exactly what it is designed to do and nothing else, even in a case of attack. Secure MANET enables reliable routing: privacy of communication with immediate degree of authentication of the parties of the information exchange process.

Sybil Attack: When one adversary node uses several identities to multiply its ability of rating other nodes in MANET.

Trust: A subjective probability of a one peer (trustee) so that particular actions of another peer (trusted) they are willing and capable to perform will be done according to trustee's expectations in the given context and time

VANET: A form of mobile ad hoc network, to provide communications among nearby vehicles and between vehicles and nearby fixed equipment, usually described as roadside equipment.

Chapter XXIX
Trust Management and Context-Driven Access Control

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ABSTRACT

The increasing diffusion of wireless portable devices and the emergence of mobile ad hoc networks promote anytime and anywhere opportunistic resource sharing. However, the fear of exposure to risky interactions is currently limiting the widespread uptake of ad hoc collaborations. This chapter introduces the challenge of identifying and validating novel security models/systems for securing ad hoc collaborations, by taking into account the high unpredictability, heterogeneity, and dynamicity of envisioned wireless environments. We claim that the concept of trust management should become a primary engineering design principle, to associate with the subsequent trust refinement into effective authorization policies, thus calling for original and innovative access control models. The chapter overviews the state-of-the-art solutions for trust management and access control in wireless environments by pointing out both the need for their tight integration and the related emerging design guidelines, that is, exploitation of context awareness and adoption of semantic technologies.

INTRODUCTION

Wireless telecommunication systems and the Internet are converging towards an integrated distributed environment that permits users to access/share services and to collaborate anytime and anywhere even when they are on the move. The increasing diffusion of portable devices with wireless connectivity and the emergence of mobile ad hoc networks (MANET) further promote opportunistic and temporary resource sharing by enabling mobile users in physical proximity of each other to spontaneously form ad hoc communities without the need to rely on the availability of a fixed network infrastructure. Mobile file sharing, mobile e-campus, emergency response, and vehicle coordination are just few collaborative application examples that illustrate the novel opportunities leveraged by envisioned and converged wired-wireless networks of the future. Hereinafter we will indicate this integrated network computing scenario formed by fixed Internet hosts, wireless terminals and wireless access points in between, as well as by collections of wireless mobile hosts forming MANET without the aid of any established fixed infrastructure, with the comprehensive term of *wireless Internet*.

However, the fear of exposure to risky interactions (possibly compromising confidentiality, availability, and integrity of both data and services) is currently limiting the widespread uptake of anywhere and anytime collaboration. To some extent, the above risk is present in any traditional distributed collaborative setting, but the wireless Internet exacerbates the perception of that risk because of the complex security challenges arising from the increased degree of openness and dynamicity of the scenario. Collaborating participants often cannot be statically preidentified; they usually change frequently due to high mobility and/or occasional failures, forming continuously varying ad hoc coalitions with entities entering and leaving groups dynamically. At the same time, roaming participants are often interested in establishing opportunistic collaborations with dynamically discovered partners, without having previous knowledge or long-term pre-established relationships with them. One of the most difficult security challenge in these environments is how to decide who to trust in the plethora of opportunistically discovered entities. In addition, MANET introduce a further level of complexity to secure collaborative applications: differently from traditional fixed networks where dedicated nodes support basic networking functions, for example, routing, in MANET these functions are carried out by available peers in the network, and there is no reason to assume that these peers will all cooperate uniformly. For instance, because network operations consume energy, some nodes may exhibit a selfish behavior and deny their cooperation, thus leading to severe degradation of network performance and functioning.

To protect and/or provide incentives for anywhere and anytime collaborations, there is the need for appropriate security models/systems that should follow novel design guidelines to take into account the high unpredictability, heterogeneity, and dynamicity of wireless Internet environments. In those scenarios where identities/roles of collaborating entities are difficult to be a-priori established, we claim that the concept of trust should become a primary design principle for the engineering of secure collaborative applications (Cahill, Gray, Seigneur, Jensen, Yong, Shand, *et al.*, 2003; Capra, 2004; Kagal, Finin, Joshi, 2001; Ruohomaa & Kutvonen, 2005). Trust provides a means to reduce the exposure to risky transactions in unfamiliar environments with no possibility to offer absolute protection against potential dangers. Trust solutions allow entities to decide whether to accept or refuse the dangers presumably associated with interactions with other entities. How to access resources and to whom to grant permissions should depend on the trust degree that collaborating entities mutually have.

Using trust as the basis to support secure ad hoc collaborations requires the design of novel trust management frameworks that enable entities to form, maintain, and evolve trust opinions in highly dynamic wireless environments. In fact, the wireless Internet deployment scenario poses complex issues to trust management and requires rethinking traditional solutions based

on assumptions that are unacceptable in these environments (Cahill et al., 2003; Capra, 2004). In fact, in traditional distributed systems trust decisions can be delegated to centralized and trusted third parties with full visibility and control over the whole trust management domain (most entities are fixed and statically known). On the contrary, in the wireless Internet the lack of both a globally available trust management infrastructure and clearly defined administrative boundaries calls for fully decentralized and self-organized trust solutions. Moreover, trust management solutions are effective as far as it is possible to bind trust opinions to security decisions. We claim that trust management should be considered as the key starting point for subsequent refinement of trust into security policies related to authorization and security management. In particular, authorization can be seen as the outcome of the refinement of trust relationships among strangers (Grandison & Sloman, 2000).

Therefore, the issue of access control is also crucial for the provisioning of anytime and anywhere collaborative applications, and raises challenges similar to trust management, thus calling for novel access control models. Only few proposals are starting to emerge in that research area, by addressing two main needs. A primary requirement is to design/develop access control solutions that take into account heterogeneity and dynamicity of available services, computing devices, and user characteristics. Along this direction, the emerging design guideline for novel access control solutions advocates a paradigm shift from subject-centric access control models to context-centric ones (Covington, Long, Srinivasan, Dey, Ahamad, & Abowd, 2001; Corradi, Montanari, & Tibaldi, 2004; Ko, Won, Shin, Choo, & Kim, 2006; Toninelli, Montanari, Kagal, & Lassila, 2006). Hereinafter, at a high abstraction level, the term "context" is defined as any information that is useful for characterizing the state or the activity of an entity or the world where this entity operates (Dey, Abowd, & Salber, 2001). Differently from subject-centric solutions where context is an optional element of policy definition, simply used to restrict the applicability scope of the permissions assigned to the subject, in context-centric solutions context is the first-class principle that explicitly guides both policy specification and enforcement; it is not possible to define a policy without the explicit specification of the context making the policy valid. The second main requirement is the full integration of novel trust models/solutions with trust-dependent (possibly context-aware) access control policies. That integration represents the most significant goal in the state-of-the-art research in security for ad hoc wireless collaborations, with currently only a very few proposals at an early stage.

The achievement of secure, open, and dynamic wireless collaborations requires not only proper trust and access control models, but also shared and interoperable vocabularies for trust and access control specifications to avoid inconsistent interpretations. Some initial research efforts tend to propose the adoption of ontological technologies as a significant guideline toward common policy understanding (Kagal, Finin, & Joshi, 2003; Tonti et al., 2003; Uszok, Bradshaw, & Jeffers, 2004). Semantically rich representations of trust and access control policies permit resource/context descriptions at different levels of abstraction and enable reasoning about both structure and properties of entities, context, and operations, thus enabling flexible opportunities for policy analysis, conflict detection, and harmonization. It is worth noticing that current security solutions for wireless Internet collaborations represent interesting steps forward, but are still more proof-of-concept prototypes of single aspects rather than comprehensive methodological and technical reference guides.

The goal of the chapter is to survey the most relevant support solutions in the literature by considering the two primary research directions emerging in the area, that is, trust management and semantic context-driven access control. In particular, examples of solutions in each category will be presented in the Trust Management section and the Semantic Context-driven Access Control section, respectively. The COMITY Framework section will focus on the main design choices of our trust-dependent context-aware middleware proposal, with the aim of exemplifying the main concerns and solution guidelines about the integration of trust and access control management. Primary open issues and expected directions of evolution end the chapter.

TRUST MANAGEMENT

The adoption of the concept of trust as the basis for engineering secure collaborative applications is currently attracting relevant research interests. Trust has always been an important element in the establishment of relationships in many fields. Humans use trust daily to promote interaction and to accept risk in situations where they have only partial information (Cahill et al., 2003). In computing, the need for trust models and support systems has recently grown with the widespread Internet usage where transactions involve entities spanning a range of domains and organizations, not all of which may be trusted to the same extent. Recently, trust issues have taken on more urgency due to wireless environments of emerging relevance populated by a plethora of unknown and anonymous users/devices. Entities can interact as far as they are able to autonomously assess trust and to use this as the basis for automated decision making, for example, whether to use a service or whether to permit access to resources.

Incorporating trust in wireless Internet systems is important because trust can be an enabling technology for application provisioning in open and dynamic environments in situations where we are given up complete control because traditional security solutions are inadequate or even inapplicable. For instance, certificate-based authentication and authorization mechanisms exhibit several limitations when deployed over ad hoc wireless scenarios. First, they impose too much computational overhead (especially due to certificate validation), often intolerable for mobile devices with limited computational resources. Second, the transient nature of ad hoc collaborations does not justify the efforts of going through the laborious and expensive certificate issuance process. Finally, the lack of central authority and network infrastructure in MANET, coupled with the dynamic nature of the network topology, complicates the adoption of certificate-based authentication and authorization mechanisms.

Trust-related research has been carried out along several different directions and has proposed many approaches for trust definition, formation, evolution, and management, but has not yet achieved universally accepted techniques/tools, as detailed in the following.

Trust Definition and Properties

Trust is a complex and multifaceted notion relating to belief in the honesty, truthfulness, competence, and reliability of a trusted person or service (Grandison & Sloman, 2000). Currently there is no consensus in the literature on the meaning of trust though several research activities recognize its importance. Due to the fact that trust is an integral part of human nature, it is normally treated as an intuitive and universally understood concept. However, by realizing that it is unwise to assume it is an intuitive, universal, and well-understood concept, many researchers have proposed different definitions of trust and the importance of trust standardization is widely recognized (Frank & Peters, 1998; Gambetta, 2001; Marsh, 1994; Staab, 2004). However, trust definitions vary depending on researcher background and on addressed application domain.

Despite these differences, most proposals result in having common basic properties. Trust is usually specified in terms of a relationship between two entities that specifies the expectation of one trust-assigning entity, called the trustor, about the actions of another entity (object of a trust estimation), that is, the trustee, within a specified context (Grandison & Sloman, 2000). Entities bound by a trust relationship may be completely or partially unknown to each other.

Trust relationships may differentiate depending on the number of entities involved. They include one-to-one relationships between two entities, one-to-many in the case of one entity that needs to trust a group, many-to-many in the case, for example, of a committee, or many-to-one in the case of departments trusting a head branch. In any case, trust relationship is asymmetric: trustor and trustee do not need to have similar trust in each other even if they exploit the same information as their basis to establish their trust relationship. This derives from the observation, common to all trust definition proposals, that trust is a subjective notion (Cahill et al., 2003).

A crucial characteristic of trust, especially in wireless collaborative environments, is that trust is context-specific, that is, trust attributes depend on the context where trust is evaluated. For instance, honesty might be more significant for financial applications, whereas competence could be relevant for medical applications. In addition, the trust level determined in one context does not directly transfer to another application domain.

Trust is also inherently linked to risk, typically with an approximate inverse relationship, where risk is the probability of loss with respect to an interaction (English, Terzis, & Wagealla, 2004; Josang & Presti, 2004; Marsh, 1994; Sloman, 2004). The riskier an activity is, the higher is the trust level required to engage in the activity. The analysis of the exact relationship between risk and trust is a key issue for enabling cooperation, but there is still little work on risk analysis within trust management models.

Trust Management Systems

Trust management is the activity of collecting, codifying, analyzing, evaluating, and reevaluating evidence that relates to trust attributes with the purpose of making assessments and decisions about trust relationships. Several solutions have been proposed, each tailored to specific computing environments and focusing only on a subset of trust management problems (Ruohomaa & Kutvonen, 2005; Srinivasan, Teitelbaum, Liang, Wu, & Cardei, in press). The aim of this section is not to provide an exhaustive survey of all trust management systems, but to overview some exemplar state-of-the-art solutions along their historical evolution to point out how and to what extent they can address the heterogeneity and dynamicity of targeted wireless environments. The section also examines the recent trust-related MANET research work and outlines the novel research directions in the field of trust management that provide useful guidelines for the design of appropriate models to secure wireless ad hoc collaborations.

The issue of trust has been initially studied in the area of distributed systems where it has been faced in close association with authentication and authorization. Trust between entities is typically established by means of credentials, such as digital certificates, that act as proofs of either the identity of credential owners or the membership of credential owners to a trusted group. For instance, a digital certificate issued by a certification authority proves that a public key is owned by a particular entity. The certification authority vouches for the authenticity of the key owner's identity. Credential-based trust management solutions are designed to verify the authenticity of credentials and to determine whether certain credentials are sufficient for performing a certain action, that is, to decide how much to trust a given credential or its issuer/owner (Blaze, Feigenbaum, & Keromytis, 1998; Blaze, Feigenbaum, & Lacy, 1996; Chu, Feigenbaum, LaMacchia, Resnick, & Strauss, 1997). These approaches, however, have some limitations. They do not precisely define how trust is built and do not provide any model/tool to support trust formation and evolution. For instance, PolicyMaker and KeyNote focus on access control issues based on credential attributes rather than on trust evolution and reasoning issues. In addition, these trust management solutions usually assume a static form of trust. Moreover, traditional approaches can be only deployed in centrally administered settings with mostly fixed and known entities where a centralized trusted authority stores information about involved entities (Blaze et al., 1996, 1998).

To overcome the aforementioned limitations, trust solutions have recently evolved to better take into account the characteristics of open and dynamic environments. The Sultan trust management framework provides a wider notion of trust and allows the specification, analysis, and management of complex trust relationships. In particular, it includes a language for describing trust and recommendation relationships (Grandison & Sloman, 2003). In the Sultan model, a trustor can specify whether a trusted entity can perform (or not) actions when associated with a specific trust level within a specific context. The trust level is a measure of belief in the honesty, competence, security, and dependability of the trustee; the context defines the conditions to satisfy to establish the trust relationship. The proposed approach requires

keeping track of historical information about entity behaviors and is based on a central server where trust information is stored and used for decision making and analysis.

A step further to better address the open and dynamic nature of wireless collaborative scenarios is represented by trust management solutions specifically designed to deal with incomplete knowledge and uncertainty. They all exploit the concepts of recommendation and reputation to enable trust decision making. The approach described by Abdul-Rahman and Hailes (2000) improves traditional solutions by proposing a distributed trust model that allows entities to autonomously reason about trust, without relying on a central authority. Based on direct experiences and recommendations, an entity derives its own trust evaluations. Mui et al. (2001) introduce a trust computational model, based on a Bayesian formalization of distributed rating processes, that takes into account the concept of reputation. The SECURE (secure environments for collaboration among ubiquitous roaming entities) project proposes another trust management solution, based on recommendations, that addresses how entities in unfamiliar environments can overcome initial suspicion to provide secure collaboration (Cahill et al., 2003). The model dynamically builds trust from local trust policies, based on past observations and recommendations. A different approach for mobile environments not relying on any third-party trusted entity is presented by Capra (2004): the proposed model enables nodes to form their trust opinions on the basis of aggregated trust information, mainly based on direct experiences regarding past interactions with neighbor nodes.

MANET push to the extreme the dynamicity, heterogeneity, and uncertainty about the execution environment, thus requiring further improvements to the design of trust management solutions to secure collaborative applications. The previously sketched solutions rely on historical reputation and recommendation to derive appropriate trust levels. In MANET, entities are likely to have only one-shot encounters, thus making difficult to collect sufficient historical reputation data about their past behavior for an appropriate trust level evaluation. In addition, due to the high variability of MANET scenarios, even if two entities re-encounter and collaborate, the collected historical data about one entity's reputation may refer to a completely different deployment context, thus making historical data less relevant to be the only aspect to consider for calculating the appropriate trust level for the new interaction context.

Other solutions in the literature have recently proposed trust models specifically targeted to MANET, in particular to deal with MANET node selfishness. For example, nodes can make trust-guided decisions to choose the appropriate relay node for forwarding packets. Several relevant activities have focused on MANET reputation, defined as the perception of one node regarding the performance of another node during the execution of a protocol (Srinivasan et al., 2007). Several reputation schemes have been proposed to mitigate selfishness. CONFIDANT (cooperation of nodes - fairness in distributed ad-hoc. networks) proposes a reputation system for misbehavior detection in MANET based on a modified Bayesian estimation approach (Buchegger & Le Boudec, 2002): everyone maintains a reputation rating and a trust rating about everyone else of interest. The reputation value of a node is calculated based on direct observation and trusted second-hand reputation messages. If a node observes another node not participating correctly, it reports this observation to other nodes that then perform actions to avoid being affected and to punish the "bad" node, for example, by refusing to forward its traffic. The approach is fully distributed and no static agreement is necessary. CORE (collaborative repuation) proposes another reputation mechanism to enforce node cooperation in MANET (Michiardi & Molva, 2002). CORE uses a collaborative monitoring technique and measures reputation as a node contribution to network operations. The OCEAN (observation-based cooperation enforcement in ad hoc networks) proposal uses only direct first-hand observations of other nodes behavior in contrast to CONFIDANT and CORE (Bansal & Baker, 2003). OCEAN discards second-hand reputation information because such information is considered subject to false accusations and requires maintain-

ing trust relationships with other nodes. Liu, Joy, and Thompson (2004) allows a MANET node to form and maintain a trust level value with each other node, based on node behavior over time. The model relies on a collaborative scheme among nodes and exploits the trust value to determine a secure routing path for message forwarding and delivery. Parker et al. (2006) propose a solution that applies only to a laboratory setting, and relies on a reputation management system to give MANET nodes the ability to independently evaluate trust of nodes which they interact with. The reputation model neither relies on any wired infrastructure nor assumes continuous connectivity among all devices; the model only assumes that every device can assign an accuracy degree to any information provided to other peers and that every node maintains trust degrees for a subset of their peers.

Partially related to trust management MANET solutions, there is also the relevant issue of intrusion detection, which is however out of the scope of this chapter. For a comprehensive survey on the various interesting proposals available in the literature about MANET intrusion detection, please refer to Anantvalee and Wu's (in press) work.

To end the section with extremely recent and just opened research directions in trust management, some activities are focusing on risk analysis aspects relating to trust. Integrated management of risk and trust is still at an early stage with only few proposals. The SECURE project incorporates an explicit risk model for assessing collaborations (Cahill et al., 2003; Carbone, Nielsen, & Sassone, 2003; Dimmock, 2003; Josang & Presti, 2004), analyzes the relationship between risk and trust, and derives a computational model integrating the two concepts; risk is used to deduce trust. An opposite approach is taken by English et al. (2004) and Quercia, Hailes, and Capra (2006) where it is trust that drives the determination of risk: based on trust assessment input, the proposed decision model estimates the probability of potential risks associated with an action, and consequently decides whether to carry out requested actions. Dimmock, Bacon, Ingram, and Moody (2005) propose a risk model based on utility theory and evaluates it in a peer-to-peer collaborative scenario to drive trust-based access control.

SEMANTIC CONTEXT-DRIVEN ACCESS CONTROL

The design and deployment of wireless Internet collaboration services impose new challenges to distributed resource retrieval and operation, undermining several assumptions of traditional collaborative solutions. Whereas traditional collaboration relies on a static characterization of context where changes in the set of both service clients (users/devices) and accessible resources are relatively rare and predictable, user/device mobility causes frequent changes in physical user location, accessible resources, and the visibility/availability of collaborating partners. Therefore, traditional subject-centric access control solutions exhibit some limitations when applied to wireless ad hoc collaborations. The tight coupling of principal identities/roles with operating conditions, needed in subject-centric access control, would require security administrators to foresee all contexts where each collaborating principal/role is likely to operate. In wireless environments where entities are typically unknown and where operating conditions frequently change even unpredictably, that traditional approach may lead to a combinatorial explosion of the number of policies to write, force a long development time, and induce potential bugs. The traditional subject-centric approach also lacks flexibility: new access control policies need to be designed and implemented from scratch for any new principal and for any principal when new context situations occur.

The emerging guideline proposed in several recent security solutions is to tightly bind context awareness and access control models. By drawing inspiration from role-based access control (RBAC), which exploits the role concept as a mechanism for grouping subjects based on their properties, context can provide a level of indirection between entities requesting resource access and their permitted set of actions. Instead of assigning permissions directly to subjects and defining in which contexts these permissions are valid, for each resource system administrators should define the context where to enable operations on it. When an entity operates in a specific context, it automatically acquires the

ability to perform the set of actions active for the current context; when context changes, entities are instantaneously granted/denied access to resources accordingly. For instance, let us suppose that a printer can only be accessed by people located in the same room the printer is. Then, whenever a person leaves that room, the person looses the permission.

The integration of access control with context has two main characteristics. First, it is an example of an active access control model (Georgiadis, Mavridis, Pangalos, & Thomas, 2001). Active security models are aware of the context associated with an ongoing activity; that distinguishes the passive concept of permission assignment from the active concept of context-based permission activation. Second, the exploitation of context as a mechanism for grouping policies and for evaluating applicable ones simplifies access control management by both increasing policy reuse and simplifying policy update and revocation.

The explicit consideration of context for access control decisions is a very recent research direction that is attracting increasing interest, but only a few context-dependent policy model proposals have currently emerged. Covington et al. (2001) strongly point out the relevance of context. The proposal allows policy designers to represent contexts through a new type of role, called *environment role*. Environment roles capture relevant environmental conditions, used to restrict and regulate user privileges. Permissions are assigned to roles (both traditional and environment ones) and role activation/deactivation regulates resource access. However, the proposed model considers a very limited set of context information represented by environment properties and states. Environment roles do not provide any means for representing other kinds of contexts, such as current collaborative activities, or user movements.

An attempt of extending these kinds of contexts is proposed by Neumannb and Strembeck (2003). They present a context-based security approach using special purpose RBAC constraints. A context constraint is defined as a dynamic RBAC constraint that checks the actual values of one or more context attributes. Accordingly, context constraints are used to define conditional permissions, that is, RBAC permissions constrained by context situations. In this security model, access rights are granted to users if corresponding context constraints are satisfied. This approach also presents an engineering process for context constraints, based on goal-oriented requirement engineering: the first step is to fetch the model of the current deployment scenario, by identifying goals and obstacles; each goal is then examined to derive the context attributes needed to describe that goal; then, goals are used to specify context constraints. Although context is considered crucial, the proposal continues to follow a subject-centric approach where context conditions act simply as constraints on privilege applicability.

Another effort of exploiting context for access control decisions is presented by McDaniel (2003). Conditions in access control policy statements are not defined as expressions over a fixed set of attributes, but viewed as general purpose programs used to measure context (every condition is a parametric function). This extended condition view embraces the environment dynamicity and allows expression of complicated relationships between context conditions. However, in this approach the policy infrastructure only evaluates policies in response to the trigger of user-requested operations; the access control process is still subject-based.

Corradi et al. (2004) propose a context-based access control management system for ubiquitous environments that dynamically determines the contexts of mobile users and rules the access to resources by taking into account user contexts. In particular, access control policies are defined as association rules between a set of permissions and a set of contexts.

By specifically focusing on access control in spontaneous wireless coalitions, Liscano and Wang (2005) propose a delegation-based approach, where users participating in a communication session can delegate a set of their permissions to a temporary *session role*, in order to enable transitory access to the resources of all participants in the session. In particular, one user assigns the session role to the entities the user is willing to communicate with. Context is used to define the conditions that

must hold for the assignment to take place. Only a limited set of contextual information can be specified and no semantic technologies are exploited to represent either session role or context constraints. In addition, security problems may arise whenever an entity delegated to play the session role leaves the collaborative session. In fact, unless the user explicitly states she is leaving the session, there is no way for the framework to be aware that the session role must be revoked.

Semantic Access Control Policies

Access control policies can be specified in many different ways and multiple approaches have been proposed in different application domains (Tonti et al., 2003). Anyway, there are some general requirements that any policy representation should satisfy regardless of its field of applicability: expressiveness to handle the wide range of possible management requirements, simplicity to ease policy definition tasks for administrators with different degrees of expertise, enforceability to ensure a mapping of policy specifications into implementable policies for various platforms, scalability to ensure adequate performance, and analyzability to enable reasoning about policies. The challenge is to achieve a suitable balance among the objectives of expressiveness, computational tractability, and ease of use.

An important principle that is currently emerging for novel access control models for wireless Internet environments is the adoption of semantically-rich policy representations to improve expressiveness, analyzability, and interoperability. A semantic-based approach allows description of contexts and associated policies at a high level of abstraction, in a form that enables their classification and comparison. This feature is essential, for instance, in order to detect conflicts between policies before their enforcement. In addition, semantic techniques can provide the reasoning features needed to deduce new information from existing knowledge. This ability may be exploited by policy frameworks when faced with unexpected situations to react in a contextually appropriate way. For example, let us consider an access control policy granting access to the projector in the meeting room of a company. Suppose that meetings are normally scheduled until 5 p.m. and that access to the projector is consequently not allowed after that time. Let us now suppose that a meeting goes beyond its scheduled end time. In this example, we need to "instruct" the system such that, if certain context conditions hold, the meeting is still taking place and access to the projector should therefore continue to be allowed.

The importance of adopting a semantic approach to the specification of all security policy building elements (subjects, actions, context, ect.) has recently emerged in well-known policy frameworks, such as KAoS (knowledgeable agent-oriented system) (Uszok et al., 2004) and Rei (Kagal et al., 2003), which have adopted semantic technologies due to their rich expressiveness and tractability.

However, the integration of semantic technologies within context-driven access control is still at its infancy with only a few proposals. In fact, a major drawback of the approaches mentioned in the previous section is that they do not exploit semantic information describing contexts, which could provide various advantages to context-aware access control systems. On the contrary, Toninelli et al. (2006) present a novel semantic-based access control model that exploits context awareness to control resource access and to enable dynamic policy adaptation in response to context changes, while adopting semantic technologies for context/policy specification to enable reasoning about context and policies. Ko et al. (2006) propose an approach that allows to overcome the semantic gap between contexts specified in policies at design time and context data dynamically collected in the execution environment. For instance, consider an authorization policy stating that a doctor working in a pediatrics ward can access information about the infants' parents. If Doctor Green is currently located in Room 209, and Room 209 belongs to a pediatrics ward, then the authorization policy should apply to Doctor Green. Semantic-based policy rules are therefore used to explicitly state the semantic relationship between the condition expressed in the policy and the condition revealed by sensors, for example, the doctor's location.

THE COMITY FRAMEWORK

COMITY (context-based middleware for trustworthy services) is our original proposal of trust-dependent access control framework that exploits semantic-based context descriptions for collaborative applications over MANET. In particular, COMITY allows different actors, sharing little or no prior knowledge about each other, to establish trustworthy relationships and to define proper access control policies governing operations on shared resources depending on mutual trust relationships. Let us note that COMITY largely exploits context awareness to model trust and access control policies. In addition, it adopts semantic-based context/policy descriptions to provide expressive representation and reasoning over trust relationships and access control policies.

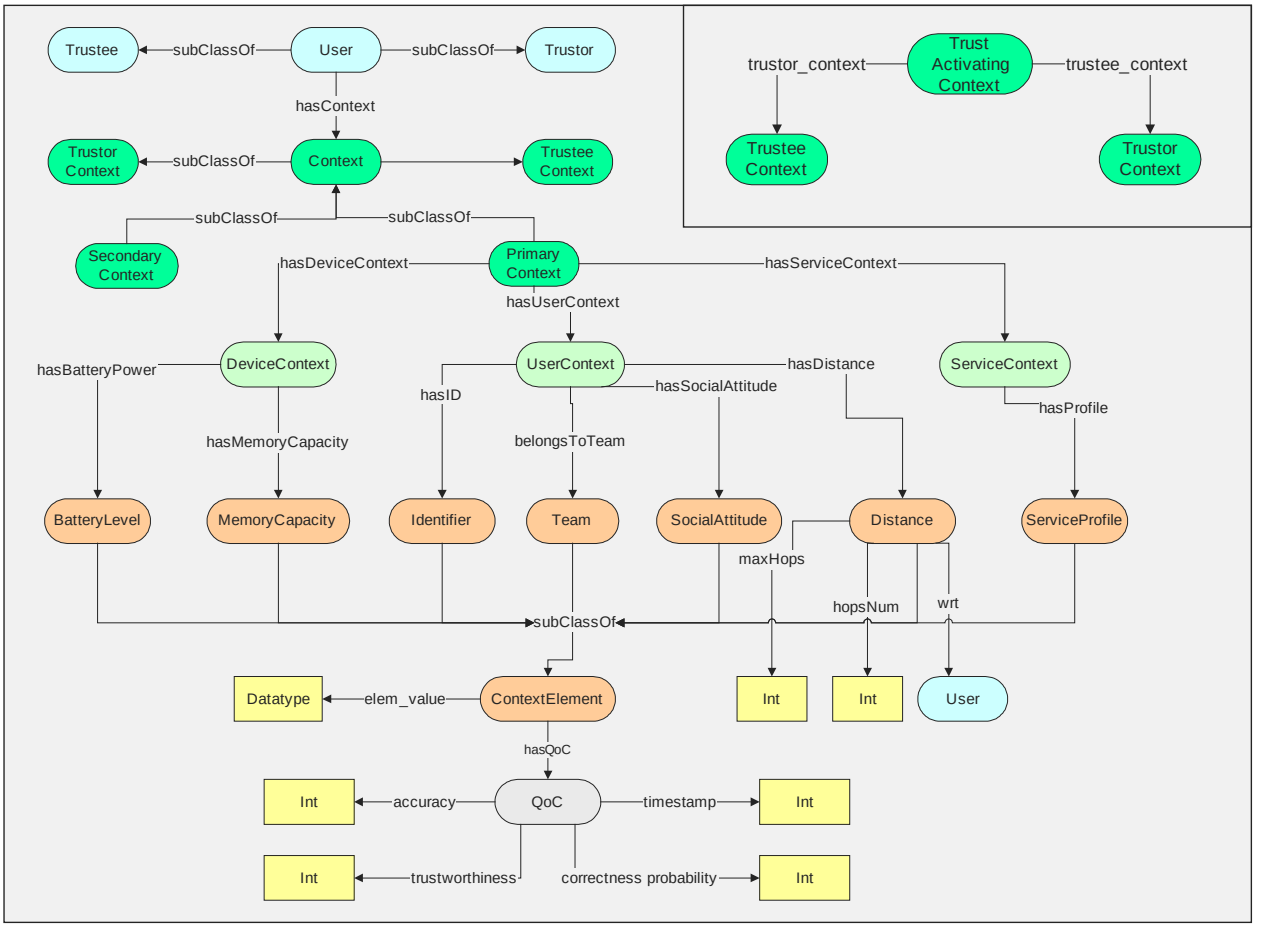
We claim that the COMITY framework is a good exemplification of an emerging trend for novel security solutions based on semantic technologies, on context awareness, and on the trust concept to properly handle highly dynamic environments. To point out those emerging solution guidelines, the following section provides a rapid overview of the main characterizing COMITY features.

COMITY Context Model

COMITY defines context as any characterizing information about the controlled entities and their surrounding environment that is relevant for establishing trust relationships and trust-dependent access control policies. The COMITY context model distinguishes between the concepts of entity and context. An entity "bears" one or more contexts and a context "inheres in" one or more entities. COMITY contexts may be either primary or secondary (see Figure 1). The primary context identifies the set of information about a collaborating entity/device (and its resources/services) to determine an initial level of trust; this set of information should be always acquirable, without the need to rely on a fixed network infrastructure for its validation. The secondary context includes context data that may not be always available, but that can be used, if available, to refine the initial trust level, such as credentials and historical data about one entity's behavior. For instance, credentials, such as digital certificates, are often available in traditional execution environments, but may not be verifiable in MANET, in that case becoming useless to determine the first level of trust. The idea underpinning our choice of distinguishing primary and secondary context is to base initial trust decisions mainly on context information that can be always acquired, for example, user characteristics, device properties, and offered services. In addition, in wireless ad hoc collaborations, users tend to discover partners of interest and to create group aggregations on the basis of user preferences/interests, offered resources/services, and access terminal capabilities, that is, on the basis of primary context.

More in details, as depicted in Figure 1, one user's primary context includes data about the user, the user's offered services, and the characteristics of the currently used access device. In particular, the User Context represents user characteristics and includes various types of context element parts. The Identifier part represents the unique system-level user identifier, for example, a personal identifier that does not convey information qualifying user identity. The Social Attitude part represents the user willingness to cooperate, that is, the user's attitude to share information with other entities. A user may declare oneself *selfish* when the user denies cooperation, for instance by not providing a service/information to save device battery degradation; *ignorant* when the user disposition is not declared; and *cooperative* when the user is willing to cooperate. The Team part specifies the team, that is, a group of users with common characteristics, if any, that the user belongs to. For instance, in the case of temporary unavailability of one collaborating service provider, this context information facilitates entities to discover other entities possibly replacing it within the team. The Distance part represents the physical distance between two entities. In particular, distance is the number of network hops required for an entity to route a message to the collaborating entity which the distance context part is associated with. The need for this context information relies on the fact

Figure 1. The COMITY model for primary and secondary contexts



that MANET users tend to prefer collaborating with close peers due to typical link instability and high error rates in message delivery in long routing paths.

The secondary context includes all other types of information characterizing users/devices and provided services that are considered relevant, but not necessary, for determining the initial trust level. For instance, user identities/roles, digital certificates, reputations, and recommendations are all information that COMITY takes into account as secondary context. Differently from primary context, COMITY does not provide any static prebuilt classification for secondary context elements; the classification of secondary context data is usually tailored to application-specific requirements and network deployment conditions at runtime.

It is worth noticing that in highly dynamic MANET scenarios there are several problems arising in context determination and processing. A primary complexity is due to frequent context changes. Due to dynamic context variations, not only the value of a context attribute is of interest, but also the moment when the value was determined (van Sinderen et al., 2006). In addition, context sources are generally restricted in their ability to estimate the precise value of a context attribute. Another factor of complexity stems from the possible unreliability of the context information provided by collaborating entities. An entity may

purposely provide incorrect information (malicious entity), may be unable to guarantee a reliable level of provided information (ignorant entity), may provide correct information (cooperative entity), or may have correct information but denies to make it available (uncooperative).

To deal with such aspects, COMITY adopts the notion of quality of context (QoC), as defined by Buchholz, Kupper, and Schiffers (2003) and van Sinderen et al. (2006), which is metainformation "that describes the quality of information that is used as context information." In particular, each context element is associated with a parameter that indicates the accuracy (i.e., the difference between the value of the context attribute and the aspect of reality it represents), the probability of correctness (the probability, estimated by the context source, to be the correct value), the trustworthiness (the probability, estimated by the context receiver, that the context source provided the correct value), and the freshness (the age of the context value, typically represented by a timestamp). Let us note that the determination of the correct QoC levels to apply in highly dynamic wireless environments is a challenging issue, in particular to achieve the most suitable tradeoff between minimum intrusiveness and accuracy. These mechanisms are currently under investigation in COMITY where we are experimenting and validating novel highly decentralized and localized techniques based on collaborative game theory.

COMITY Trust Model

There are different forms of trust in the literature relating to whether access is being provided to trustor's resources, the trustee is providing a service, trust concerns authentication, or it is being delegated (Grandison & Sloman, 2000). The COMITY trust model focuses on two specific aspects: an entity A (trustor) trusts an entity B (trustee) i) to use resources that A owns or controls, and ii) to provide a service not requiring access to A's resources.

COMITY defines trust relationships as one-to-one associations between contexts and trusted actions, with each relationship characterized by a specific trust degree. Contexts act as intermediaries between A and B and the set of operations for which A trusts B. COMITY users exploit the primary and secondary context described in the previous section to define their own trust relationships. In particular, the context involved in a trust relationship definition is the intersection between A's and B's contexts (hereinafter called *trust activating context*, see Figure 1). This means that an action is considered trusted if executed within the scope of specific conditions of the applicable trust activating context. Which trustor and which trustee are involved in the trust relationship is directly derived from the identifier parts of the two primary contexts involved in the trust activating context intersection.

COMITY trust relationships have all an associated trust degree, which reflects the trustor opinion about the trustworthiness of executing an action within the scope of its associated trust activating context. We are currently integrating COMITY with existing trust models in the literature suitable to derive trust degree values in decentralized MANET environments (Capra, 2004; Quercia et al., 2006). In general, trust degree determination depends on various factors. For instance, the need perceived by A of letting B to perform the specified action on either A's or B's resources influences trust degree calculation; that need may be quantified as the expected loss deriving from not executing the specified action. In addition to need, it is necessary to take into account QoC levels and the risk of the loss deriving from performing critical actions in an incorrect way.

COMITY Trust-Dependent Access Control Model

COMITY uses trust-dependent access control policies to govern operations on resources when A trusts B to use resources that A owns or controls. In this case, A has to define suitable authorization policies. On the contrary, in the case A trusts B to provide a service that does not involve access to A's resources, B's usage of the service is outside A's control, but depends on the access control policies defined by B. Both A and B follow the COMITY

trust-dependent access control model to define proper access control policies.

The COMITY trust-dependent access control model extends our approach proposed by Toninelli et al. (2006). In particular, the access control model is context-centric: contexts are associated with allowed actions that represent all and only the conditions that enable access to the resources. By drawing inspiration from Java protection domains (Gong, 1999), we call these contexts as *protection contexts*: they are determined by policies and provide users with a controlled visibility of the performable resource access actions.

The COMITY extension we are currently working on consists in exploiting the trust degree as a specific protection context with possibly associated actions. In other words, it is possible to allow/deny an action as far as the resource access requestor has a proper trust degree. More in details, at any resource access request, COMITY verifies whether a trust activating context has been defined for the requested operation. In that case, COMITY checks whether the trust activating context is currently in effect (*active context*), that is, the context defining conditions match the operating conditions of the requesting entity, requested resource, and environment. In particular, there is the need to verify whether the requestor is the trustee indicated in the trust activating context. Then, the corresponding trust degree associated with the activating trust context and with the requested operation is used to select the proper access control policy.

Context and Trust Relationship Implementation

The COMITY context model is based on an underlying system model that describes interactions by using the concepts of entities and actions. An entity represents any actor/resource in the system and is logically characterized by a number of properties expressed as attribute-value pairs. An action describes an activity that an actor is able to perform on another entity. An interaction is the association of an entity and an action.

COMITY adopts description logics (DL) and associated inference mechanisms to model entities, actions, trust activating contexts, trust relationships, and access control policies. In particular, we use Web ontology language (OWL)-based ontologies, as shown in Figure 2a (for the sake of simplicity, we use hereinafter a compact DL notation). A trust activating context is defined as a subclass of a generic context. Each generic context consists of several context elements, with each element characterized by at least an identity property and a location property defining the physical or logical position of an entity, and eventually by other additional properties. A trust activating context is defined by restriction on the trustor and trustee primary contexts (possibly by considering also secondary contexts when available). Each primary context consists of several context elements, grouped within a specific context category, with each element characterized by a value and at least a QoC attribute.

Figure 2a shows an example of a trust activating context, where the trustee is within two-hop distance from the trustor and has a device with a full battery; both trustor and trustee are cooperative. Each information associates with values of trustworthiness and/or freshness. Figure 2b shows an example of trust-dependent access control policy. The trust relationship defines an association between the trust activating context shown in Figure 2a (Trust_Activating_Context_1) and the action of the trustee accessing the files included in folder(A). COMITY assigns a level of trust (70%) to this association. The access control policy states that access to folder(A) files is granted to a trustee if the trust level associated to that action reaches the minimum threshold of 60%. Therefore, Trust_Activating_Context_1 is effective and the trustee is granted with the requested permission.

The DL adoption in context modeling and reasoning has well-known benefits. For instance, when considering activating contexts as classes and a set of sensor inputs as individuals, DL-based reasoning allows one to determine which activating contexts are in effect by verifying which trust activating context classes the current state is an instance of, and to figure out how activating contexts relate to each other, for example, via nesting [6]. For instance, let us consider the case of a user

Figure 2. COMITY specifications for trust relationship and trust-based access control policy

Trustor Primary Context Specification

```
Trustor_Primary_Context_1 ≡ Primary_Context ⊓
                            ∃has_User_Context.Trustw_Coop_UserCtx
Trustw_Coop_UserCtx ≡ UserContext ⊓ ∃hasSocialAttitude.Cooperative_T10
Cooperative_T10 ≡ Social_Attitude ⊓ ∃elem_value.{"Cooperative"} ⊓ ∃trustworthiness.{10}
```

Trustee Primary Context Specification

```
Trustee_Primary_Context_1 ≡ Primary_Context ⊓ ∃hasUserContext.Trustw_Coop_2Hops_UserCtx
                            ∃hasDeviceContext.FullBattery_DeviceCtx
Trustw_Coop_2Hops_UserCtx ≡ UserContext ⊓ ∃hasSocialAttitude.Cooperative_T8 ⊓
∃hasDistance.Max2Hops
Max2Hops ≡ Distance ⊓ ∃maxHops.{2} ⊓ ∃wrt.Trustor
Cooperative_T8 ≡ Social_Attitude ⊓ ∃elem_value.{"Cooperative"} ⊓ ∃trustworthiness.{8}
FullBattery_DeviceCtx ≡ DeviceContext ⊓ ∃hasBatteryPower.FullBattery_T8_TS67
FullBattery__T8_TS67 ≡ BatteryLevel ⊓ ∃elem_value.{"Full"} ⊓ ∃trustworthiness.{8} ⊓
```

Trust Activating Context Specification

```
Trust_Activating_Context_1 ≡ Trust_Activating_Context ⊓ ∃trustor_context.Trustor_Primary_Context_1
                             ⊓ ∃trustee_context.Trustee_Primary_Context_1
```

A)

Context-based Trust Relationship Specification

```
FileA_Access_Trust_Rel ≡ Trust_Association ⊓ ∃activating_context.Trust_Activating_Context_1 ⊓
                         ∃trusted_action.FileA_Sharing_Action ⊓ ∃trust_degree.TrustDegree_70%
FileA_Access_Action ≡ AccessAction ⊓ ∃target.FolderA_Files ⊓ ∃performedBy.Trustee
TrustDegree_70% ≡ TrustDegree ⊓ ∃hasTrustValue.{70%}
```

Trust-dependent Access Control Policy Specification

```
FileA_Access_Policy ≡ Access_Control_Policy ⊓ ∃controls. FileA_Access_Action ⊓
                      ∃protection_context.MinTrustDegree_60%
MinTrustDegree_60% ≡ Trust_Degree ⊓ ∃hasMinValue.{60%}
```

B)

who has a PDA with full battery, is self-defined as cooperative, and is one-hop far from a trustor. By means of DL-based reasoning, COMITY can automatically recognize that this enables the trustee part of the trust activating context defined in Figure 2a.

CONCLUSIONS AND OPEN RESEARCH ISSUES

Securing ad hoc wireless collaborations is a complex management issue that calls for novel security paradigms suitable for high heterogeneity and dynamicity. In this perspective, trust is starting to be recognized as an enabling principle for promoting cooperation among (partially) unknown entities. However, trust is insufficient for securing wireless Internet collaborations and there is the need to associate it with proper resource access control policies.

In addition, in the specific field of trust management, novel solutions have started to emerge specifically designed to deal with uncertainty and incomplete knowledge that are usual in dynamic wireless environments. However, despite the widespread interest, the field is still immature. Sound terminological and methodological frameworks are still missing, there is not even a commonly agreed definition of the concept of trust, and several aspects still require investigation, such as the proper evaluation and combination of trust and risk.

Also the relationship between context and trust has not received the needed attention whereas it is crucial to form trust opinions and to reason about recommendation and reputation. The relationship is twofold. First, trust, recommendation, and reputation opinions can be context-dependent. Second, context elements at the time when trust, recommendation, and reputation opinions are created should be compared with the trustor's context where interactions currently take place. Moreover, there is the need to integrate trust management solutions with run-time monitoring both to support self-adaptation of trust opinions to dynamic variations and to detect (and possibly react to) violations to the initially estimated trust level.

Another open research issue is about mechanisms and strategies to promote cooperation among possibly unknown entities in dynamic environments: credit systems on top of trust management solutions could reward the good behavior of cooperating peers and punish selfish/cheating nodes. A very relevant research challenge at the moment is the full integration of novel trust-based management models/solutions with trust-dependent (possibly context-aware) access control policies. Finally, there is the need for standardization efforts, based on semantic technologies, to open new possibilities for entities to represent contexts, trust relationships, and access control policies in a fully interoperable way, which is crucial in open and dynamic deployment scenarios.

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KEY TERMS

Access Control: The ability to limit and control the actions/operations that a legitimate user of a computer system can perform. Access control constrains what a user can do directly, as well what programs executing on behalf of a user are allowed to do.

Context: Many definitions of context are available in the literature (Dey et al., 2001). The most accepted one defines "context" as any information useful for characterizing the state or the activity of an entity or the world in which this entity operates. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves.

Middleware for Distributed Systems: A distributed software support layer which abstracts over the complexity and heterogeneity of the underlying distributed environment with its multitude of network technologies, operating systems, and implementation languages. The primary role of middleware is to ease the task of developing, deploying, and managing distributed applications by providing a simple, consistent, and integrated distributed programming environment.

Recommendation: A communicated opinion about the trustworthiness of a third party entity.

Reputation: The opinion that one entity builds about another entity. In particular, reputation refers to the general expectation about the future actions of an entity based upon past actions. Reputation can be exploited in trust management by providing one relevant element to consider for the trustor to assess the prospective trustee's trustworthiness.

Semantic Technologies: Technologies that permit to add semantic metadata to information resources. Semantic metadata allow to effectively process data, for instance via automated inferences, that is, understanding what a data resource is and how it relates to other data independently of its name and syntax.

Trustee: The entity (individual, access terminal, resource/service component) that is the object of a trust evaluation by a trustor (see the following definition).

Trust Management: The collection, maintenance, and processing of the information required to make a trust relationship decision, to evaluate the criteria related to trust relationships, and to monitor and re-evaluate existing trust relationships. The term was first defined by Blaze et al. (1996) as a unified approach to specifying and interpreting security policies, credentials, and relationships in order to allow direct authorization of security-critical actions.

Trustor: An individual who sets up a trust or, in other words, the subject that has the possibility/responsibility to trust a target entity.

Chapter XXX
A Survey of Key Management in Mobile Ad Hoc Networks

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ABSTRACT

Security has become a primary concern in mobile ad hoc networks (MANETs). The characteristics of MANETs pose both challenges and opportunities in achieving security goals, such as confidentiality, authentication, integrity, availability, access control, and nonrepudiation. Cryptographic techniques are widely used for secure communications in wired and wireless networks. Most cryptographic mechanisms, such as symmetric and asymmetric cryptography, often involve the use of cryptographic keys. However, all cryptographic techniques will be ineffective if the key management is weak. Key management is also a central component in MANET security. The purpose of key management is to provide secure procedures for handling cryptographic keying materials. The tasks of key management include key generation, key distribution, and key maintenance. Key maintenance includes the procedures for key storage, key update, key revocation, key archiving, and so forth. In MANETs, the computational load and complexity for key management are strongly subject to restriction by the node's available resources and the dynamic nature of network topology. A number of key management schemes have been proposed for MANETs. In this chapter, we present a survey of the research work on key management in MANETs according to recent literature.

INTRODUCTION

Mobile Ad Hoc Networks (MANETs)

In areas where there is little communication infrastructure or the existing infrastructure is inconvenient to use, wireless mobile users may still be able to communicate through the formation of *mobile ad hoc networks* (Perkins, 2001). A mobile ad hoc network, or simply MANET, is a collection of wireless mobile hosts that form a temporary network without the aid of any centralized administration or support. In such a network, each mobile node operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may be multiple hops away from each other.

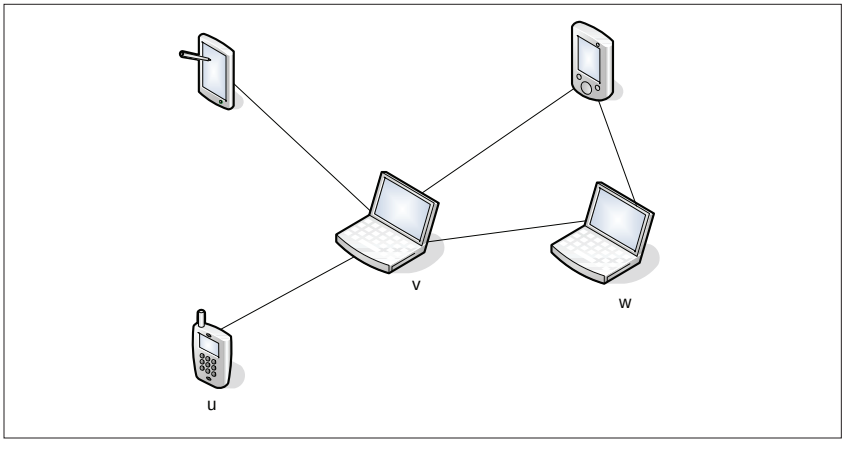
Possible applications of MANETs include: soldiers relaying information for situational awareness on the battlefield; business associates sharing information during a meeting; attendees using laptop computers to participate in an interactive conference; and emergency disaster relief personnel that are coordinating efforts at sites of fires, hurricanes, or earthquakes.

A routing protocol is necessary in such an environment, since two hosts that wish to communicate may not be able to exchange packets directly. Figure 1 shows a simple example of a MANET. Host *w* is not within the range of host *u*'s wireless transmitter and vice versa. If *u* and *w* wish to exchange packets, they may depend on the services of host *v* to forward packets for them because *v* is within the overlap between *u* and *w*'s transmission range. Although the number of hops for a host to reach another is likely to be small, the routing problem in a real MANET will still be complicated due to the inherent nonuniform propagation characteristics of wireless transmissions, and the highly dynamic topology of the networks.

Characteristics of MANETs

A MANET is an autonomous system of mobile nodes. The system may operate in isolation, or may have gateways to an interface with a fixed network. Its nodes are equipped with wireless transmitters/receivers using antennas that may be omnidirectional (broadcast), highly directional (point-to-point), or some combination thereof. At a given time, the system can be viewed as a random graph due to the movement of the nodes and their transmitter/receiver coverage patterns, the transmission power levels, and the cochannel interference levels (Karygiannis & Owens, 2002; Ravi, Raghunathan, & Potlapally, 2002; Stallings, 2002). The network topology may change with time as the nodes move or adjust their transmission and reception parameters. Thus, ad hoc networks have several salient characteristics:

Figure 1. An example of a mobile ad hoc network



- **Dynamic topologies:** The network topology may change randomly and rapidly at unpredictable times, and may consist of both directional and unidirectional links. Nodes freely roam in the network, join or leave the network at their own will, and fail occasionally.
- **Resource constraints:** The wireless links have significantly lower capacity than wired links. The computation and energy resources of a mobile device are limited.
- **Infrastructure-less:** There is no well-defined infrastructure, or access point, or some other central control point available. Moreover, the wireless medium is accessible by both legitimate nodes and attackers. There is no clear boundary to separate the inside network from the outside world.
- **Limited physical security:** Portable devices are generally small with weak protection. The physical devices could be stolen or compromised.

Security Challenges Overview

Security Attacks

While MANETs can be quickly and inexpensively setup as needed, security is a more critical issue compared to wired networks or other wireless counterparts. Many *passive* and *active* security attacks could be launched from the outside by malicious hosts or from the inside by compromised hosts (Lou & Fang, 2003; Murthy & Manoj, 2005; Wu, Chen, Wu, & Cardei, 2006).

- **Passive attacks:** In passive attacks, an intruder captures the data without altering them. The attacker does not modify the data and does not inject additional traffic. The goal of the attacker is to obtain information that is being transmitted, thus violating the message confidentiality. Since the activity of the network is not disrupted, these attacks are difficult to detect. A powerful encryption mechanism can alleviate these attacks, making it difficult to read the transmitted data.
- **Active attacks:** In active attacks, an attacker actively participates in disrupting the normal operation of the network services. An attacker can create an active attack by modifying packets or by introducing false information. Active attacks can be further divided into internal and external attacks; internal attacks are from compromised nodes that were once a legitimate part of the network. Since the adversaries are already part of the network as authorized nodes, they are much more severe (Wu et al., 2006) and difficult to detect compared to external attacks. External attacks are carried by nodes that are not a legitimate part of the network. Such attacks are often prevented through firewalls or some authentication and encryption mechanisms.

Security Goals

Security services include the functionality that is required to provide a secure networking environment. It comprises *authentication*, *access control*, *confidentiality*, *integrity*, *nonrepudiation*, and *availability* (Ilyas, 2003; Nichols & Lekkas, 2002; Wu et al., 2005; Yang, Luo, Ye, Lu, & Zhang, 2004). Authentication is the ability to verify that a peer entity in an association is the one it claims to be, or can be used for the determination of data origins. Availability ensures the survivability of the network service despite denial-of-service attacks. Confidentiality ensures that certain information is never disclosed to unauthorized entities. Integrity guarantees that a message being transferred is not corrupted. Nonrepudiation ensures that the origin of a message cannot deny having sent the message. Access control is the ability to limit and control access to devices and/or applications via communication links. The main security services can be summarized as follows:

- **Authentication**: The function of the authentication service is to verify a user's identity and to assure the recipient that the message is from the source that it claims to be from. First, at the time of communication initiation, the service assures that the two parties are

authentic, that each is the entity it claims to be. Second, the service must assure that a third party does not interfere by impersonating one of the two legitimate parties for the purpose of authorized transmission and reception.

- **Confidentiality**: Confidentiality ensures that the data/information transmitted over the network is not disclosed to unauthorized users. Confidentiality can be achieved by using different encryption techniques such that only legitimate users can analyze and understand the transmission.
- **Integrity:** The function of integrity control is to assure that the data are received exactly as sent by an authorized party. That is, the data received contain no modification, insertion, deletion, or replay.
- **Access control**: This service limits and controls the access of a resource such as a host system or application. To achieve this, a user trying to gain access to the resource is first identified (authenticated) and then the corresponding access rights are granted.
- **Nonrepudiation:** This is related to the fact that if an entity sends a message, the entity cannot deny that it sent that message. If an entity gives a signature to the message, the entity cannot later deny that message. In public key cryptography, a node A signs the message using its private key. All other nodes can verify the signed message by using A's public key, and A cannot deny the message with its signature.
- **Availability:** This involves making network services or resources available to the legitimate users. It ensures the survivability of the network despite malicious incidences.

Security Mechanisms

Cryptography is an important and powerful tool for secure communications. It transforms readable data (plaintext) into meaningless data (ciphertext). Cryptography has two dominant categories, namely symmetric-key (secret-key) and asymmetric-key (public-key) approaches (Saloma, 1996). In symmetric-key cryptography, the same key is used to encrypt and decrypt the messages, while in the asymmetric-key approach, different keys are used to convert and recover the information. Although the asymmetric cryptography approaches are versatile (can be used for authentication, integrity, and privacy) and are simpler for key distribution than the symmetric approaches, symmetric-key algorithms are generally more computation-efficient than the asymmetric cryptographic algorithms (Tanenbaum, 2003). There are varieties of symmetric and asymmetric algorithms available, including data encyrption standard (DES), advanced encryption standard (AES), international data encryption algorithm (IDEA), RSA, and EIGamal (Menezes, Oorschot, & Vanstone, 1996). Threshold cryptography is another cryptographic technique that is quite different from the above two approaches. In Shamir's (k, n) secret sharing scheme, secret information is split into n pieces according to a random polynomial. Meanwhile, the secret could be recovered by combining any threshold k pieces based on Lagrange interpolation. These cryptographic algorithms are the security primitives that are widely used in wired and wireless networks. They can also be used in MANETs and help to achieve the security in its unique network settings.

Key Management

As in the above description, cryptography is a powerful tool in achieving security. However, most cryptosystems rely on the underlying secure, robust, and efficient key management subsystem. In fact, all cryptographic techniques will be ineffective if the key management is weak. Key management is a central part of the security of MANETs. In MANETs, the computational load and complexity for key management are strongly subject to restriction by the node's available resources and the dynamic nature of network topology. Some asymmetric and symmetric key management schemes (including group key) have been proposed to adapt to the environment of MANETs. Key management deals with key generation, key storage, distribution, updating, revocation, deleting, archiving, and using keying materials in accordance with security policies. In this chapter, we present a comprehensive survey

of research work on key management in MANETs based on recent literature. This chapter is organized as follows: The introduction gives an introduction of MANETs. The key management section discusses key and trust models in wired networks and MANETs. The asymmetric key management section presents the asymmetric key management schemes in MANETs. The symmetric key management section in MANETs presents the symmetric key management schemes in MANETs. The group key management section presents the group key management in the infrastructure networks with proper extension being necessary for MANETs. We conclude the chapter and discuss possible future work in the open challenges and future directions section. We include the reference and key terms at the end of the chapter.

KEY MANAGEMENT IN MANETS

Key management is a basic part of any secure communication. Most cryptosystems rely on some underlying secure, robust, and efficient key management system. Secure network communications normally involve a key distribution procedure between communication parties, in which the key may be transmitted through insecure channels. A framework of trust relationships needs to be built for authentication of key ownership in the key distribution procedure. While some frameworks are based on a centralized trusted third party (TTP), others could be fully distributed. For example, a certification authority (CA) is the TTP in asymmetric cryptosystems, a key distribution center (KDC) is the TTP in the symmetric system, and in pretty good privacy (PGP) no TTP is assumed. According to recent literature, the centralized approach is regarded as inappropriate for MANETs because of the dynamic environment and the transient relationships among mobile nodes. Most researchers prefer the decentralized trust model for MANETs. Several decentralized solutions have been proposed in recent papers with different implementations, such as how the CA's responsibility is distributed to all nodes, or to a subset of nodes.

Fundamentals of Key Management

Cryptographic algorithms are security primitives that are widely used for the purposes of authentication, confidentiality, integrity, and nonrepudiation. Most cryptographic systems require an underlying secure, robust, and efficient key management system. Key management is a central part of any secure communication and is the weakest point of system security and the protocol design.

A key is a piece of input information for cryptographic algorithms. If the key was released, the encrypted information would be disclosed. The secrecy of the symmetric key and private key must always be assured locally. The key encryption key (KEK) approach (Burnett & Paine, 2001) could be used at local hosts to protect the secrecy of keys. To break the cycle (use key to encrypt the data, and use key to encrypt key) some noncryptographic approaches need to be used, for example, smart card, biometric identity (such as fingerprint), and so forth.

Key distribution and key agreement over an insecure channel are at high risk and suffer from potential attacks. In the traditional digital envelop approach, a session key is generated at one side and is encrypted by the public-key algorithm. Then it is delivered and recovered at the other end. In the Diffie-Hellman (DH) scheme (Burnett & Paine, 2001), the communication parties at both sides exchange some public information and generate a session key on both ends. Several enhanced DH schemes have been invented to counter man-in-the-middle attacks. In addition, a multiway challenge response protocol, such as Needham-Schroeder (Tanenbaum, 2002), can also be used. Kerberos, which is based on a variant of Needham-Schroeder, is an authentication protocol used in many real systems, including Microsoft Windows. However, in MANETs, the lack of a central control facility, the limited computing resources, dynamic network topology, and the difficulty of network synchronization all contribute to the complexity of key management protocols.

Key integrity and ownership should be protected from advanced key attacks. Digital signatures, hash functions, and the hash function-based message

authentication code (HMAC) (Menezes et al., 1996) are techniques used for data authentication and/or integrity purposes. Similarly, the public key is protected by the public-key certificate, in which a trusted entity called the certification authority in public key infrastructure (PKI) vouches for the binding of the public key with the owner's identity. In systems lacking a TTP, the public-key certificate is vouched for by peer nodes in a distributed manner, such as PGP (Burnett & Paine, 2001). In some distributed approaches, the system secret is distributed to a subset or all of the network hosts based on threshold cryptography. Obviously, a certificate cannot prove whether an entity is "good" or "bad." However, it can prove ownership of a key. Certificates are mainly used for key authentication.

A cryptographic key could be compromised or disclosed after a certain period of usage. Since the key should no longer be usable after its disclosure, some mechanism is required to enforce this rule. In PKI, this can be done implicitly or explicitly. The certificate contains the lifetime of validity; it is not useful after expiration. However, in some cases, the private key could be disclosed during the valid period, in which case the CA needs to revoke a certificate explicitly and notify the network by posting it onto the certificate revocation list (CRL) to prevent its usage.

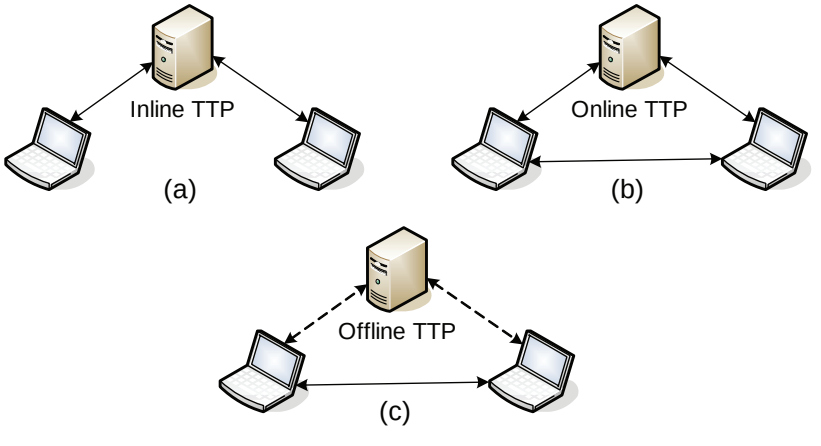
Key management for large dynamic groups is a difficult problem because of scalability and security. Each time a new member is added or an old member is evicted from the group, the group key must be changed to ensure backward and forward security. Backward security means that new members cannot determine any past group key and discover the previous group communication messages. Forward security means that evicted members cannot determine any future group key and discover the subsequent group communication information. The group key management should also be able to resist against colluded members.

Trust Models

Centralized Trust Model

For the centralized trust model, there is a well-trusted entity known as a TTP (Kaufmanet, Perlman, & Speciner, 2002; Menezes et al., 1996). A TTP is an entity trusted by all users in the system, and it is often used to provide key management services. Depending on the nature of their involvement, TTPs can be classified into three categories: inline, online, or off-line. See Figure 2 for an illustration. An inline TTP participates actively in between the communication path of two users. An online TTP participates actively but only for

Figure 2. Categories of trust third parties



management purposes, as the two parties communicate with each other directly. An off-line TTP communicates with users prior to the setting up of communication links and remains off-line during network operation.

TTPs in Symmetric Key Management Systems

TTPs have been implemented in both symmetric and asymmetric key management systems. KDC and key translation centers (KTC) (Oppliger, 1998) are TTPs in symmetric cryptographic key management systems and the CA is the TTP in public-key management systems. KDC and KTC simplify the symmetric key management since each user does not have to share a secret key with every other user. Instead, it only needs to share one key with the TTP. This reduces the total number of keys that need to be managed from $\frac{n(n-1)}{2}$ to n, where n is the total number of users. Figure 3 illustrates the protocols by implementing KDC or KTC.

1. Alice requests to share a secret key with Bob. If the TTP is KDC, it generates a key to use. Otherwise, Alice provides it. The message is encrypted using the secret key shared between Alice and the TTP.
2. The TTP encrypts the session key with the key it shares with Bob and returns it to Alice.
3. Alice sends the encrypted session key to Bob, who can decrypt it and thereafter use it to communicate securely with Alice.

Public Key Infrastructure (PKI)

The use of public key cryptography requires the authenticity of public keys. Otherwise, it is easy to forge or spoof someone's public key. Some trusted framework must be present to verify the ownership of a public key. A straightforward solution is to have any two users that wish to communicate exchange their public keys in an authenticated manner. It would require the initial distribution of *n(n-1)* public keys. Obviously, this solution is not scalable for a large network and has the same problems we discussed in the symmetric key management system. However, by having a trusted third party issue certificates to each of the users, every user only needs to hold the public key of the TTP, which significantly simplifies the authentication process for users' public keys. Actually, there are two dominating trust models in PKI, namely, centralized and web-of-trust trust models (Wu et al., 2006; Yi & Kravets, 2004). For network scalability, the centralized trust model could be a hierarchical trust structure instead of a single CA entity. Multiple CA roots could be necessary for a large

Figure 3. Establishment of session key using KDC or KTC

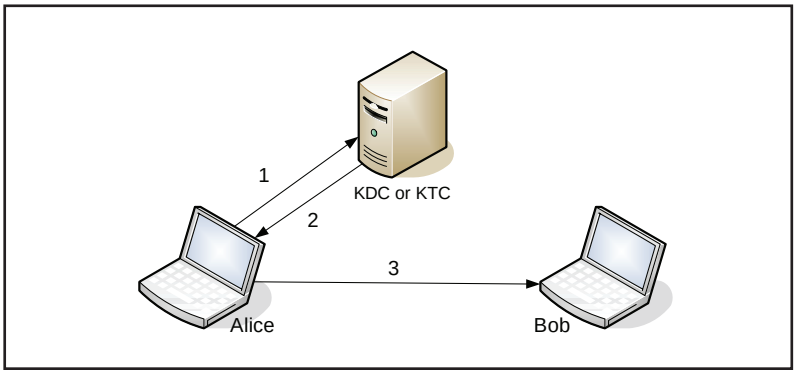
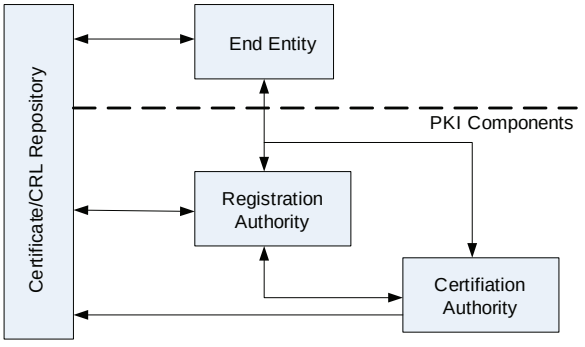


Figure 4. Components of a PKI



network, such as the Internet. We will discuss the fully distributed or web-of-trust model later.

A PKI provides the mechanisms needed to manage certificates, and normally consists of the components illustrated in Figure 4.

In this diagram, the CA is the component responsible for issuing and revoking certificates, while the registration authority (RA) is responsible for establishing the identity of the subject of a certificate and the mapping between the subject and its public key. The RA and CA can be implemented as one component; therefore, RA is an optional component. PKI components provide basic services, such as registration, initialization, certification, key update, revocation, key recovery, cross-certification, and so forth.

Web-of-Trust Model

The web-of-trust model is also called certificate chaining. PGP (Tanenbaum, 2002) is an example built on this trust model. In the web-of-trust model there is no TTP that is well-trusted by all network nodes. Instead, peer nodes can issue certificates to each other and populate the certificate graph. Certificates can be authenticated through certificate chaining. Compared with the centralized trust model, the web-of-trust model does not require a heavy infrastructure or complex bootstrapping procedures, and every node plays an identical role and shares the same responsibility. Although the web-of-trust model has the above advantages, it has two major limitations. First, a certificate graph may not populate enough to provide certificate chains for a given pair of nodes, so it is difficult to predict whether any given authentication request can be fulfilled. Second, without relying on a TTP, any trust relationship relies on the goodwill and the correct behaviors of all participants. Obviously, that cannot always be assumed. However, since there is no clear way to tell if a certificate chain includes any misbehaving nodes, the overall confidence for the certificate is relatively low.

Decentralized Trust Model

In MANETs, a framework for key management built on a fully centralized mode is not feasible, not only because of the difficulty of maintaining such a globally trusted entity but also because the central entity could become a hotspot of attacks. Thus, this network suffers from a security bottleneck. Meanwhile a completely distributed model may not be acceptable because there is no well-trusted security anchor available in the whole system. One feasible solution is to distribute the central trust to multiple entities (or the entire network) based on a secret sharing scheme. In the decentralized public key management scheme, the system public key is distributed to the entire network, while the system private key is split to multiple pieces and distributed to a subset (or all) of the nodes. The subset of group nodes creates a view of a CA and functions as a CA in combination.

Hybrid Trust Model

This scheme takes advantage of the positive aspects of two different trust systems. The basic idea is to incorporate a TTP into the certificate graph. Here, the TTP is a virtual CA node that represents all nodes that comprise the virtual CA. Some authentication metrics, such as confidence value, are introduced in order to "glue" two trust systems (Yi & Kravets, 2004). While this model is theoretically sound, it is difficult to "glue" two different trust systems since there is no clear way to assign a value of confidence level.

Overview of Key Management Schemes in MANETs

Asymmetric Key Management Schemes

Recently, research papers have proposed different key management schemes for MANETs. Most of them are based on public-key cryptography. The basic idea is to distribute the CA's functionality to multiple nodes. Zhou and Hass (1999) present a secure key management scheme by employing *(t, n)* threshold cryptography. The system can tolerate t-1 compromised servers. Luo et al., (2004, 2001) propose a localized key management scheme in which all nodes are servers and the certificate service can be performed locally by a threshold number of neighboring nodes. Yi, Naldurg, and Kravets (2002) put forward a similar scheme. The difference is that their certificate service is distributed to a subset of nodes, which are physically more secure and powerful than the others. Wu, Wu, and Dong, (in press) also introduce a scheme that is similar to Yi, in which server nodes form a mesh structure and a ticket scheme is used for efficiency. Capkun, Buttyan, and Hubaux (2003) consider a fully distributed scheme that is based on the same idea of PGP. Yi and Kravets (2004) provide a composite trust model. Their idea is to take advantage of the positive aspects of both the central and fully distributed trust models.

Symmetric Key Management Schemes

There are research papers that are based on the symmetric-key cryptography for securing MANETs. For instance, some symmetric key management schemes are proposed for sensor nodes that are assumed to be incapable of performing costly asymmetric cryptographic computations. Pair-wise keys can be preloaded into nodes, or based on the random key distribution in which a set of keys is preloaded. Chan (2004) introduces a distributed symmetric key distribution scheme for MANETs. The basic idea is that each node is preloaded with a set of keys from a large key pool (Chan, Perrig, & Song, in press; Du, Deng, Han, & Varshney, 2003). The key pattern should satisfy the property that any subset of nodes can find at least one common key, and the common key should not be covered by a collusion of a certain number of other nodes outside the subset. Chan and Perrig (2005) introduce a symmetric key agreement scheme for the sensor nodes. The basic idea of their approach is that each node shares a unique key with a set of nodes vertically and horizontally (in 2-dimensions). Therefore, any pair of nodes can rely on at least one intermediate node to establish the common key.

Group Key Management Schemes

Collaborative and group-oriented applications in MANETs are going to be active research areas. Group key management is one of the basic building blocks in securing group communications. However, key management for large dynamic groups is a difficult problem because of scalability and security (Rafaeli & Hutchison, 2003). For instance, each time a new member is added or an old member is evicted from a group, the group key must be changed to ensure backward and forward security.

ASYMMETRIC KEY MANAGEMENT SCHEMES IN MANETS

Secure Routing Protocol (SRP)

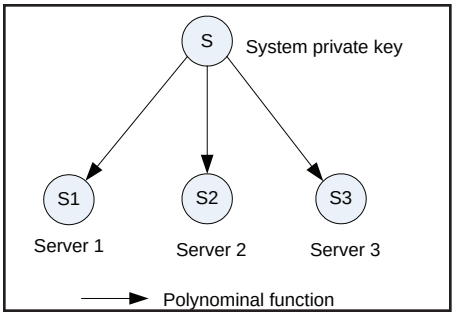
SRP is a decentralized public key management protocol proposed by Zhou and Hass (1999) by employing *(t, n)* threshold cryptography (Shamir, 1979; Wong, Wang, & Wing, 2002) in their research paper called "Securing Ad Hoc Networks." In the system, there are *n* servers, which are responsible for public-key certificate services. Therefore, the system can tolerate t-1 compromised servers. Servers can proactively refresh the secret shares using the proactive secret sharing (PSS) (Herzberg, Jarecki, Krawczyk, & Yung, 1995) techniques or by adjusting the configuration structure based on share redistribution techniques to handle compromised servers or system failure. Since the new shares are independent of the old ones, mobile adversaries would have to compromise a threshold number of servers in a very short amount of time, which obviously increases the difficulty of the success of adversaries. The system configuration of this scheme is illustrated in Figure 5. The system public key K is distributed to all nodes in the network, whereas the private key S is split to *n* shares s1, s2, s3, …, sn, one share for each server according to a random polynomial function.

In this scheme, the system model is such that *n* servers are special nodes, each with its own public/private key pair and the public key of every node in the network. This is a critical issue in a large network. However, this scheme does not describe how a node can contact *t* servers securely and efficiently in case the servers are scattered in a large area. A share-refreshing scheme is proposed to counter mobile adversaries. The update of secret shares does not change the system public/private key pairs. Therefore, nodes in the network can still use the same system public key to verify a signed certificate so that the share-refreshing is transparent to all nodes. However, a method of distributing these updated subshares to all nodes securely and efficiently in the network is not addressed.

Ubiquitous and Robust Access Control (URSA)

URSA is a localized key management scheme proposed by Luo et al. (2004, 2001) in their paper "URSA: Ubiquitous and Robust Access Control for Mobile Ad Hoc Networks". The URSA protocol is also based on threshold cryptography as in SRP (Zhou & Haas 1999). The difference between URSA and SRP is that in URSA, all nodes are servers and are capable of producing a partial certificate, while in SRP only server nodes can produce certificates. Thus, certificate services are distributed to all nodes in the network. *URSA* also proposes a distributed self-initialization phase that allows a newly joined node to obtain secret shares by contacting a coalition of *k* neighboring nodes without requiring the existence of an online secret share dealer. The basic idea is to extend the PSS technique by shuffling the partial shares instead of shuffling the secret sharing polynomials. The purpose of this shuffling process is to prevent deducing the original secret share from a resulting share.

Figure 5. Illustration of SRP scheme



In URSA, every node should periodically update its certificate. To update its certificate, a node must contact its 1-hop neighbors, and request partial certificates from a collection of threshold k number of nodes. It can combine partial certificates into a legitimistic certificate. This will introduce either communication delays or cause search failures. It could potentially utilize services from 2-hop neighboring nodes.

The advantage of this scheme is efficiency and secrecy of local communications, as well as system availability since the CA's functionality is distributed to all network nodes. On the other hand, it reduces system security, especially when nodes are not well-protected because an attack can easily locate a secret holder without much searching and identifying effort. One problem is that in a sparse network where a node has a small number of neighbors, the threshold k is much larger than the network degree d and a node that wants to have its certificate updated needs to move around in order to find enough partial certificate "producers." The second critical issue is the convergence in the share-updating phase. Another critical issue is that too great an amount of off-line configuration is required prior to accessing the networks.

Mobile Certificate Authority (MOCA)

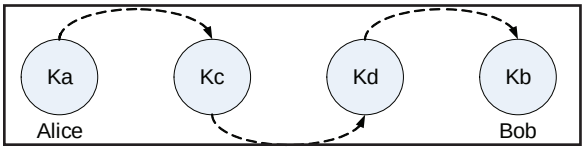
MOCA is a decentralized key management scheme proposed by Yi et al. (2002) in their paper "Key Management for Heterogeneous Ad Hoc Wireless Networks". In this approach, a certificate service is distributed to mobile certificate authority nodes. MOCA nodes are chosen based on heterogeneity if the nodes are physically more secure and computationally more powerful. In cases where nodes are equally equipped, they are selected randomly from the network. The trust model of this scheme is a decentralized model since the functionality of CA is distributed to a subset of nodes. A service-requesting node can locate $k + \alpha$ MOCA nodes either randomly, based on the shortest path, or according to the freshest path in its route cache. However, the critical question is how nodes can discover those paths securely since most secure routing protocols are based on the establishment of a key service in advance.

Self-Organized Key Management

Capkun et al. (2002) consider a fully distributed key management scheme in their paper "Self-organized Public Key Management for Mobile Ad Hoc Networks". This scheme is based on the web-of-trust model that is similar to PGP. The basic idea is that each user acts as its own authority and issues public key certificates to other users. A user needs to maintain two local certificate repositories. One is called the nonupdated certificate repository and the other one is called the updated certificate repository. The reason a node maintains a nonupdated certificate repository is to provide a better estimate of the certificate graph. Key authentication is performed via chains of public key certificates that are obtained from other nodes through certificate exchanging, and are stored in local repositories.

The fully distributed, self-organized certificate chaining has the advantage of configuration flexibility and it does not require any bootstrapping of the system. However, this certificate chaining requires a certain period to populate the certificate graph. This procedure completely depends on the individual node's behavior and mobility. One the other hand, this fully self-organized scheme lacks any trusted security anchor in the trust structure that may limit its usage for applications where high security assurance is demanded. In addition, many certificates need to be generated and every node should collect and maintain an up-to-date

Figure 6. An example of certificate chain



certificate repository. The certificate graph, which is used to model this web-of-trust relationship, may not be strongly connected, especially in the mobile ad hoc scenario. In that case, nodes within one component may not be able to communicate with nodes in different components. Certificate conflicting is another potential problem in this scheme.

Composite Key Management

Recently, Yi and Kravets (2004) provided a composite key management scheme in their paper "Composite Key Management for Ad Hoc Networks". In their scheme, they combine the centralized trust and the fully distributed certificate chaining trust models. This scheme takes advantage of the positive aspects of two different trust systems. The basic idea is to incorporate a TTP into the certificate graph. Here, the TTP is a virtual CA node that represents all nodes that comprise the virtual CA. Some authentication metrics, such as confidence value, are introduced in order to "glue" two trusted systems. A node certified by a CA is trusted with a higher confidence level. However, properly assigning confidence values is a challenging task. An example of a composite key management model is shown in Figure 7.

Secure and Efficient Key Management (SEKM)

SEKM is a decentralized key management scheme proposed by Wu and Wu (2007) in their paper "Secure and Efficient Key Management in Mobile Ad Hoc Networks". It is based on the decentralized virtual CA trust model. All decentralized key management schemes are quite similar in that the functionality of the CA is distributed to a set of nodes based on the techniques of threshold cryp-

Figure 7. An example of composite key management scheme

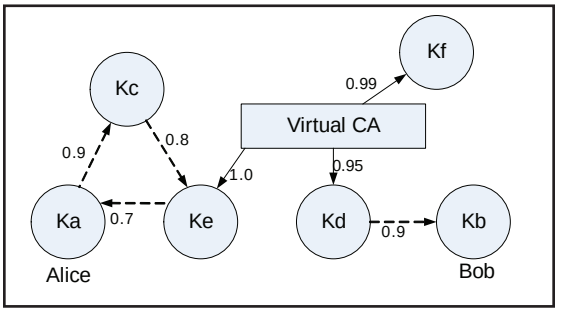
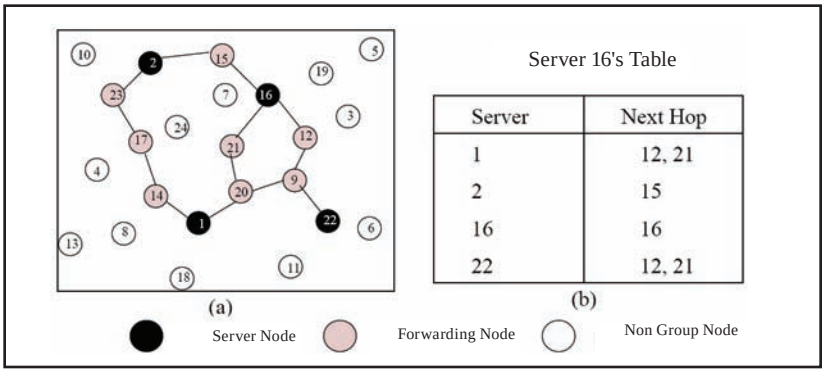


Figure 8. Server group structure in SEKM



tography. However, no schemes except for SEKM present detailed, efficient, and secure procedures for communications and cooperation between secret shareholders that have more responsibilities. In SEKM, all servers that have a partial system private key are to connect and form a server group. The structure of the server group is a mesh structure as shown in Figure 8. Periodic beacons are used to maintain the connection of the group so servers can efficiently coordinate with each other for share updates and certificate service. The problem with SEKM is that, for a large network with highly dynamic mobility, maintaining the structure server group can be costly.

SYMMETRIC KEY MANAGEMENT SCHEMES IN MANETS

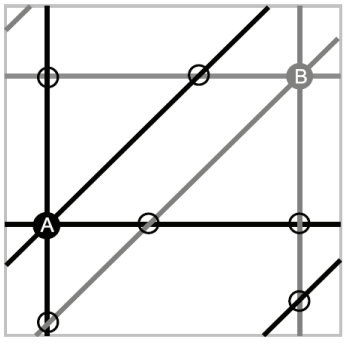
Distributed Key Predistribution Scheme (DKPS)

DKPS is a distributed symmetric key management scheme proposed by Chan (2004) in the paper "Distributed Symmetric Key Management for Mobile Ad Hoc Networks". It is aimed at the network settings where mobile nodes are not assumed to be capable of performing computationally intensive public key algorithms and the TTP is not available. The basic idea of the DKPS scheme is that each node randomly selects a set of keys in a way that satisfies the probability property of cover-free family (CFF). Any pair of nodes can invoke the secure shared key discovery procedure (SSD). The theory behind the SSD is the additive and scalar multiplicative homomorphism of the encryption algorithm as well as the property of nontrivial zero encryption. To discover the common secret key, one side of the two parties can form a polynomial and send the encrypted polynomial to the other side. The coefficients of the polynomial are encrypted with the sender's secret key. The other side will send back the encrypted polynomial multiplied by a random value. Because of the homomorphism and nontrivial zero encryption properties, either side can only discover the common secret key, without disclosing the other noncommon keys.

Peer Intermediaries for Key Establishment (PIKE)

PIKE is another symmetric key management scheme proposed by Chan and Perrig (2005) in their paper "PIKE: Peer Intermediaries for Key Establishment in Sensor Networks". It is a random key predistribution scheme. The basic idea of PIKE is to use sensor nodes as trusted intermediaries to establish shared keys. Each node shares a unique secret key with a set of nodes. In the case of 2-dimension, a node shares a unique secret with each of the $O(\sqrt{n})$ nodes in the horizontal and vertical dimensions. Therefore, any pair of nodes can have a common secret with at least one intermediate node. This key predistribution scheme can be extended to three or more dimensions. Figure 9 shows the basic idea of the PIKE scheme. Dark lines connect

Figure 9. Illustration of PIKE scheme



the nodes that share a unique key with node A, and light lines connect nodes that share a unique key with node B. There are six nodes that each share a unique key with node A and node B.

GROUP KEY MANAGEMENT APPROACHES

The messages are protected by encryption using the chosen key, which in the context of group communication is called the group key. Only those who know the current group key are able to recover the original message. Group key establishment means that multiple parties want to create a common secret to be used in the secure exchange of information. Two people who did not previously share a common secret can create one common secret with a DH key exchange protocol. The 2-party DH protocol can be extended to a generalized version of the *n*-party DH key-exchange model. Research efforts have been put into the design of group key agreement protocols to achieve better scalability, efficiency, and storage saving, such as the introduction of a tree structure and hash function. Furthermore, the group key management also needs to address the security issue related to membership changes. The modification of membership could require the group key to be refreshed (e.g., periodic rekey). The change of group keys when old members leave or new members join ensures backward and forward security. Therefore, a group key scheme must provide a scalable and efficient mechanism to rekey the group.

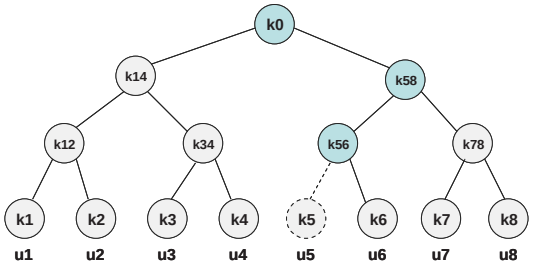
Group key management protocols can be roughly classified into three categories, namely, centralized, decentralized, and distributed (Rafaeli & Hutchison, 2003). In centralized group key protocols, a single entity is employed to control the whole group and is responsible for rekeying and distributing group keys to group members. In the decentralized approaches, a set of group managers is responsible for managing the group as opposed to a single entity being held responsible. In the distributed method, group members themselves contribute to the formation of group keys and are equally responsible for the rekeying and distribution of group keys. Recently, collaborative and group-oriented applications in MANETs have become an active research area. Obviously, group key management is a central building block in securing group communications in MANETs. However, group key management for large and dynamic groups in MANETs is a difficult problem because of the requirement of scalability and security under the restrictions of nodes' available resources and unpredictable mobility.

The literature presents several approaches to group key management. In this section, we give an overview of those protocols. Most of the following group key protocols are designed for the infrastructure networks. However, with the proper extension, some of them could be utilized and adapted to the MANET environment, or could serve as a hint for the design of MANET-specific group key management protocols. For instance, group Diffie-Hellman (GDH) and logical key hierarchy (LKH) have been extended into the MANETs. Wu, Wu, and Dong (in press) propose a simple and efficient group key management scheme, called SEGK, for MANETs. The basic idea of SEGK is that a physical multicast tree is formed in MANETs for efficiency. Group members take turns acting as group coordinator to compute and distribute intermediate key materials to group members. The keying materials are delivered through the tree links. The coordinator is also responsible for maintaining the connection of the multicast group. All group members can compute the group key locally in a distributed manner.

Logical Key Hierarchy (LKH)

LKH is a centralized group key management scheme proposed by Wallner, Harder, and Agee (1998) (Wong, Gouda, & Lam, 1998). It is based on the tree structure with each user (group participant) corresponding to a leaf and the group initiator as the root node. The tree structure will significantly reduce the number of broadcast messages and storage space for both the group controller and group members. The operation of this scheme is outlined below.

Figure 10. A sample tree structure of LKH



Each leaf node shares a pair-wise key with the root node as well as a set of intermediate keys from it to the root. So, for a balanced binary tree, each group member stores at most *d+1* keys, where *d* = $\log_2 n$ is the height of the tree, and *n* is the total number of group members. See Figure 10: U_5 stores *k5*, *k56*, *k58*, and *k0*.

When a member joins the group, the rekey procedure will be started. A rekey message is generated containing the new set of keys encrypted with its respective node's children key. Figure 10 shows keys that are affected. The new member U_5 receives a secret key *k*5 and attaches the intermediate node k56 logically. The keys *k*56, *k58,* and *k0*, which are in the path from *k5* to *k0*, need to be refreshed. New keys, *k'*56, *k'58*, and *k'*0, are generated as illustrated in Figure 11. These keys are encrypted with their respective node's children's key, for example, one instance of *k'56* is encrypted by *k5* and the other copy is encrypted by *k6* (see Figure 11). The removal of a member follows a similar procedure. For instance, when member U6 leaves the group, *k56*, *k58*, and *k0* should be changed and the new set of keys *k'56*, *k'58*, and *k'0* are encrypted with their respective children's key. See Figure 12 for an illustration of a member leave.

Figure 11. Illustration of joining member U5

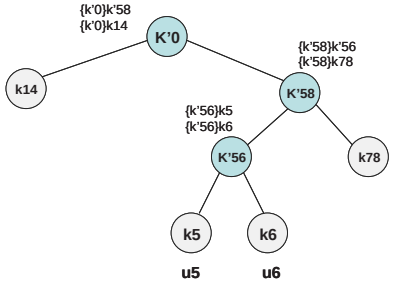
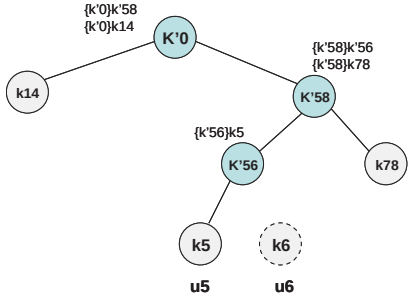


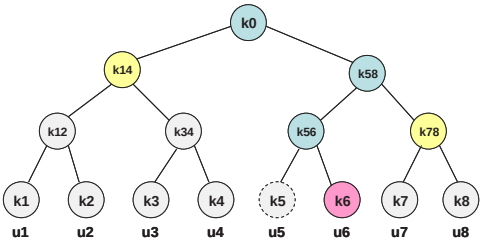
Figure 12. Illustration of leaving member U6



One-Way Function Trees (OFT)

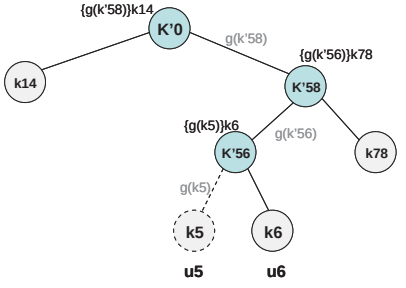
OFT is another centralized group key management scheme proposed by Sherman and McGrew (2003). It is based on the tree structure that is similar to the above LKH scheme. However, all keys in the OFT scheme are functionally related according to a one-way hash function. The idea is that the keys held by a node's children are blinded using a one-way hash function and then combined together using a mixing function, such as a bitwise exclusive-or operation. Each group user receives blind keys from its sibling set as well as the blind key of its own sibling. Based on collected blinded keys, the group users can deduce each key of its ancestor set. See Figure 13 for an illustration. *k6* is the key of U5's sibling. *k56*, *k58*, and *k0* are the keys of U5's ancestor set. *k78* and *k14* are the keys of U5's sibling set.

Figure 13. A sample tree structure of OFT



A group user still needs to store *d+1* keys, where $d = \log_2 n$ is the height of the tree, and *n* is the total number of group members. The scheme has the same complexity as the LKH scheme for a balanced tree structure, but in the rekeying process, the size of keying materials reduces from $2 \cdot \log_2 n$ to $\log_2 n$.

Figure 14. Illustration of join member U5 in OFT



The message size reduction is achieved because in the OFT scheme. The blinded key changed in a node is encrypted only with the key of its sibling node while in LKH scheme the new key must be encrypted with its two children's keys. See Figure 14.

Tree-Based Group Diffie-Hellman (TGDH)

TGDH is a group key management scheme proposed by Kim, Perrig, and Tsudik (2000a, 2000b). It is a tree-based group DH scheme. The basic idea is to combine the efficiency of the tree structure with the contributory feature of DH.

The basic operation of this scheme is as follows. Each group member contributes its (equal) share to the group key, which is computed as a function of all the shares of current group members. As the group grows, new members' shares are factored into the group key but old members' shares remain unchanged. As the group shrinks, departing members' shares are removed from the new key and at least one remaining member changes its share. All protocol messages are signed by the sender using RSA.

In TGDH, a sponsor takes a special role that can involve computing keys and broadcasting the blinded keys to the group during events of member join, leave, partition, and merge. Any member in the group can take on this responsibility. Figure 15 illustrates the operation of member join. When M_4 joins the group, sponsor M_3 will rename node <1, 1> to <2, 2>, generate a new intermediate node <1, 1> and new member node <2, 3>, and promote <1, 1> as the parent node of <2, 2> and <2, 3>. Sponsor M_3 knows blinded key $BK_{<2, 3>}$ (the blind key of newly joined member) and $BK_{<1, 0>}$, so M_3 can compute the new group key $K_{<0, 0>}$ as it can

Figure 15. Illustration of join member in TGDH

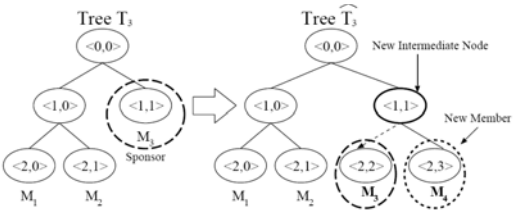
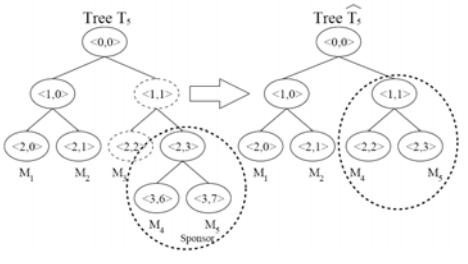


Figure 16. Illustration of leaving member in TGDH



compute the intermediate key $K_{<1, 0>}$. Any other member can also compute the new group key after sponsor M_3 publishes the blinded key of $K_{<1, 0>}$. The leave operation is quite similar. See Figure 16 for an illustration.

Group Diffie-Hellman (GDH)

GDH is a group key distribution scheme proposed by Steiner, Tsudik, and Waidner (1998). GDH

actually contains three key distribution schemes that are extended from the DH protocols. In this chapter, we only give the algorithm of GDH.3 and ignore GDH.1 and GDH.2 since these two protocols need a total of $O(n^2)$ exponentiations. The first stage involves collecting contributions from all group members (upflow). At the end of this stage, user U_{n-1} obtains $g^{\prod\{N_k|k\in[1,n-1]\}}$ and broadcasts this value to all other group members at the second stage. At the third stage, every user $U_i (i \neq n)$ factors out its own exponent and forwards the result to the last user U_n. At the final stage, U_n collects all inputs from the previous stage, raises every one of them to the power of N_n and broadcasts the resulting *n-1* values to the rest of the group. In the end, every group member has a value of the form $g^{\prod\{N_k|k\in[1,n]\wedge k\neq i\}}$ and can easily compute the group key K_n. Member addition and deletion can be handled easily in this scheme.

A simple example is shown below to illustrate the operation of this scheme for a group of four members, A, B, C, and D:

Stage 1: A→ {B}: g^a ; B→{C}: g^{ab}
Stage 2: C →{A, B, D}: g^{abc}
Stage 3: A→{D}: g^{bc} ; B→{D}: g^{ac} ; C→{D}: g^{ab}
Stage 4: D→{A, B, C}: g^{bcd} , g^{acd} , g^{abd} , $\{g^{abc}\}$
Stage 5: $K= g^{abcd}$

The total number of exponentiations of GDH.3 is *5n-6*, the total number of rounds is *n+1*, and the number of messages is *2n-1*.

Burmester-Desmedt (BD)

BD is a distributed group key management scheme proposed by Burmester and Desmedt (1994). It is an extension of the Diffie-Hellman key distribution system. The core algorithm of this scheme is as follows:

Step 1: Each group member U_i selects a random exponent r_i, and then computes and broadcasts $z_i = g^{r_i} \bmod p$.

Step 2: Each group member U_i computes and broadcasts $X_i = (\frac{z_{i+1}}{z_{i-1}})^{r_i} \bmod p$

Step 3: Each group member U_i computes the common secret: $k_i = (z_{i-1})^{nr_i} \cdot X_i^{n-1} \cdot X_{i+1}^{n-2} \ldots X_{i-2} \bmod p$.

That is, each group user will come up with the same secret $k = g^{r_1r_2+r_2r_3+\ldots+r_nr_1} \bmod p$ which is the group key shared by all group members.

In BD scheme, each group member needs to perform *n+1* exponentiations. It also requires a total number of *2n* broadcast messages. Considering a simple example with a group of four users, A, B, C, and D, in the group, user B can compute $k = (g^a)^{4b} \cdot (g^{cb}/g^{ab})^3 \cdot (g^{dc}/g^{bc})^2 \cdot (g^{ad}/g^{cd})^1 = g^{ab+bc+cd+da}$. Obviously, it can be verified that other users A, C, and D can compute the same key as B.

Skinny Tree (STR)

STR is a simple group key management scheme proposed by Steer, Strawczynski, Diffie, and Wiener (1990). It is also extended from the DH. STR requires group users to be ordered in a chain. The outline of the algorithm is the following:

Step 1: Every user generates a random number r_i, and broadcasts $g^{r_i} \bmod p$.
Step 2: Users are ordered as a chain. The first and the second user can calculate the value

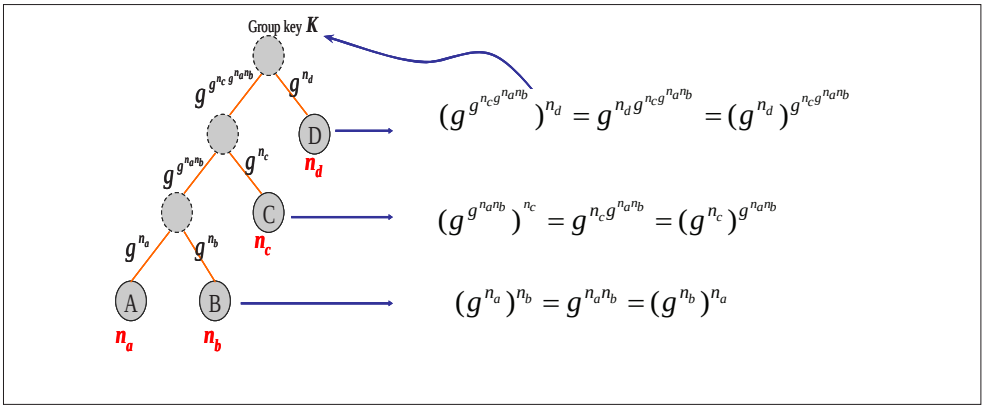
$$k = g^{(r_n g^{(r_{n-1} g^{(\ldots g^{(r_3 g^{(r_1 r_2)})})})})}$$

However, users *3* to *n* require further information to calculate *k*. The detailed algorithm as given by the author is skipped here, which can be referred by Steer et al. (1990). A simple example of four users A, B, C, and D is shown is Figure 17. This scheme takes two rounds and four modular exponentiations, which makes it suited for adding new group members. However, member exclusion is relatively difficult.

OPEN CHALLENGES AND FUTURE DIRECTIONS

Security is an important feature that determines the success and degree of deployment of MANETs. Cryptography is a powerful tool to defend against a variety of attacks and helps to achieve a variety of security goals. Most cryptographic

Figure 17. Illustration of STR



algorithms require the use of keying materials. If the cryptographic key is disclosed, then there is no security at all. Obviously, key management is in the central part of any secure communication and is the weakest point of the security. However, ensuring the security of MANETs is more challenging because of the host mobility, shared wireless medium, resource constraint of physical devices, and most seriously, lack of a fixed and trustable control point in MANETs. Designing and building an underlying secure, robust, and scalable key management system is a difficult problem that has received increased attention recently. The current research on key management in MANETs is still at its early stage.

Research on key management in MANETs goes in three directions according to the trust models, which are centralized, decentralized, and fully distributed. While centralized approaches are of least interest in MANETs, decentralized approaches have gained a lot of research attention. The fully distributed trust model is also favored for MANETs. Interestingly, a hybrid approach that combines the centralized model with the distributed scheme has been proposed recently.

Key management in MANETs can also be roughly classified into unicast and multicast key management according to the communication type. Previously, most research focused on the secure pair-wise communications, and key management focus was on how to distribute or establish a session key between a pair of communication parties. Currently, secure group communications, such as dynamic conferencing or multicasting in MANETs, is becoming an active research area. The security of group communication involves the management of group keys. For efficiency, tree-based structures are utilized when a central or virtual central control entity is available. Most contributory group key distributions are based on DH protocol with different implementations. Meanwhile, key management can also be classified into symmetric and asymmetric key management depending on the underlying cryptographic algorithms used. Currently, most key management schemes are based on asymmetric cryptosystems. However, for some specific types of MANETs, such as sensor networks, the symmetric key management scheme is dominant. An example of a symmetric approach is the random key predistribution in sensor networks.

In summary, based on different assumptions, many key management protocols have been proposed for MANETs. All key management approaches are subject to various restrictions such as the mobile device's available resources, the network bandwidth, and MANETs dynamic nature. An efficient key management protocol for MANETs is an ongoing hot research area.

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KEY TERMS

Certification Authority (CA): A trusted third party in an asymmetric cryptosystem that vouches for the binding of the public key with an identity.

Group Key: A common secret known by the group members

Key: A set of values that a cryptographic algorithm operates on

Key Distribution Center (KDC): A trusted third party in a symmetric cryptosystem that establishes a shared secret key between two parties

Key Management: The process of managing key materials in a cryptosystem which is related to key generation, storage, exchange, update, and replacement

Key Ring: A set of public or private keys used in PGP.

Mobile Ad Hoc Network (MANET): A collection of mobile hosts form a temporary network without centralized administration.

Chapter XXXI
Security Measures for Mobile Ad-Hoc Networks (MANETs)

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ABSTRACT

Mobile ad hoc networks (MANETs) have gained popularity in the past decade with the creation of a variety of ad hoc protocols that specifically offer quality of service (QoS) for various multimedia traffic between mobile stations (MSs) and base stations (BSs). The lack of proper end-to-end security coverage, on the other hand, is a challenging issue as the nature of such networks with no specific infrastructure is prone to relatively more attacks, in a variety of forms. The focus of this chapter is to discuss a number of attack scenarios and their remedies in MANETs including the introduction of two entities; ad hoc key distribution center (AKDC) and decentralize key generation and distribution (DKGD), which serve as key management schemes.

INTRODUCTION

There are two classes of attacks on a network: *passive* and *active* attacks. In passive attacks, the intruder poses as an observer and only audits the information exchanged between communicating parties, without any intervention. Whereas in active attacks, the intruder actually takes part actively and performs actions such as additions, deletions, or delays.

The most basic requirements of a secure system should prevent common passive and active attacks, through the following functionalities:

- **Confidentiality:** Confidentiality or *privacy* is the ability to secure the content of the information communicated between authorized parties. When confidentiality is in place, the intruder should not be able to recover any information (part of the definition for pas-

sive attacks). In a broader sense, an intruder should not be able to determine the parties involved or whether a communication session occurred (anonymous routing). There are two levels of confidentiality:

- **Data confidentiality:** In which the unauthorized users are unaware of the existing protected data and their nature. This is further subcategorized as:
  - *Confidentiality of existing protected information*
  - *Confidentiality of protected data exposure*
- **Address confidentiality:** Which hides the identity of participating parties

- **Data integrity:** Integrity of data ensures the authorized recipient that data have not been altered in any sense, including addition, deletion, and undue delays. This requires data authentication. The following scenarios are associated with data integrity:
  - **Unauthorized modification protection:**Protecting against any illegitimate alteration.
  - **Detection of unauthorized protected data modification:** Detecting that a protected data has been modified in an unauthorized manner.
  - **Detection of a data deletion in a sequential order:** In a serial transmission (one bit at a time), it is important to detect if any part of the transmission has been deleted.
- **Authentication:** Authentication is a very important security requirement, which provides the facility to verify the identity of parties taking part in a communication. There are three types of authentication procedures (Kargl, 2006):
  - **Entity (user) authentication:** This type of authentication is used to authenticate an entity or a device to make sure entities wishing to communicate with other parties in the communication range are the ones they claim to be, such as people, clients, and servers.
  - **Geo-authentication:** In this type of authentication, the location of the nodes or any information about locations are to be verified and authenticated.
  - **Attribute authentication:** This is the process of establishing confidence in an attribute that applies to a specific device or entity.
  - **Data authentication:** Authentication of data is the ability of the authorized parties to ascertain the authenticity of data received from other authorized parties.
- **Nonrepudiation:** This is the ability to prevent an authorized user from denying the involvement in previous communications or activities. This is further subcategorized as follow:
  - **Protection against sender denial:** Protecting the receiver from the send er's denial that the data were sent by the sender.
  - **Protection against forward denial:** Protecting against the denial of forwarding entities on the path, disputing their forwarding actions.
  - **Protection against delivery denial:** Protecting against the delivery dispute of the data to the final destination.
  - **Protecting against receiving denial:** Protecting the sender from the recipient's denial of the fact that it has ever received the data.
- **Access control:** Access control is a mean for enabling the legitimate user to have access to the resources. Access control uses one or more of the other security mechanisms for granting access to the communications channel and/or applications. The following scenarios are categorized under access control:
  - **User identification:** Access control uti lizes user-authentication to grant access for legitimate individuals.

- **Emergency access:** Accessing emergency procedures (i.e., disaster relief) is part of the access control scheme, where normal access procedures are interrupted with high-priority emergency access procedures.
- **Data encryption/decryption:** Privacy and data integrity procedure calls are used to perform user- and application-dependent encryption/decryption schemes.
- **Automatic logoff/logon:** Shutting down a part or parts of the network due to security breaches, is the task for access control. Granting access permission to those parts is also within acces control tasks.

- **Availability**: Availability is a probabilistic measure of entities being available for possible communication upon request. The higher the probability of communication entities being available, the stronger and more secure the communication channel is. Denial-of-service (DoS) causes less availability of the channel, therefore DoS and availability are opposite definitions.

LAYERED ATTACKS

Active attacks could be further categorized in a layered attack fashion (see Figure 1 and Table 1), since most security systems obey the open system interconnection (OSI) model, it is a common practice to discuss the types of attacks according

Figure 1. Active-layered attacks (Adapted from Manoj & Murthy, 2005)

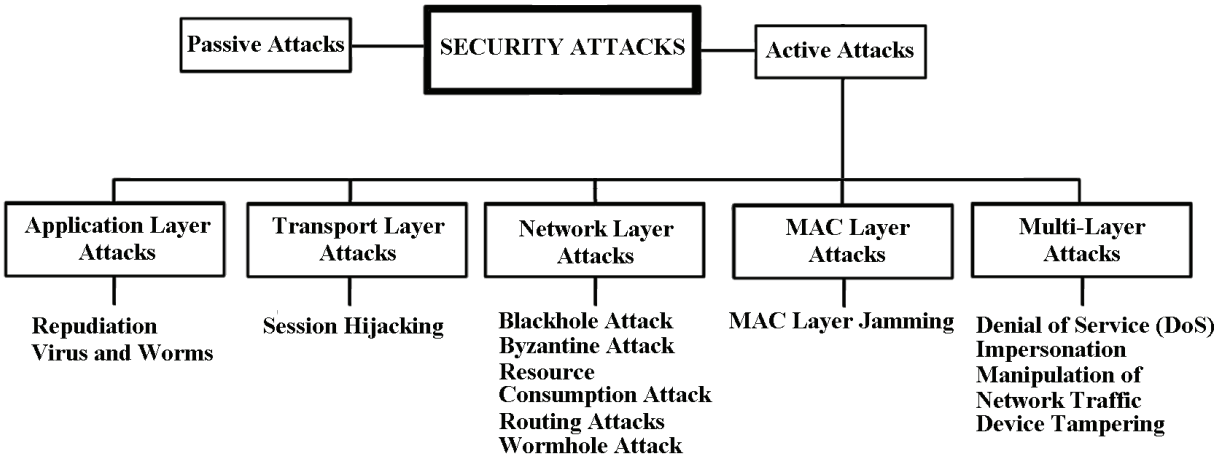


Table 1. Definition of a few active-layered attacks

DoS	Denial of service attack is a multilayer attack issue, which has the most impact on the physical layer, where communication signals are exposed to everyone and interfering (or interference) with the radio waves is the first step in DoS attack. Except for electromagnetic shielding (which can only limit the interferences) and physically securing the transmitters, there is not much to be done to prevent physical layer attacks. Fortunately for an effective physical attack, the intruder has to either have physical access to the network (tamper with the wired-infrastructures) or be physically close to the transmitters (in wireless-infrastructures). Therefore one can locate the infrastructures as distant as possible, or construct physical shielding around the transmitters.

continued on following page

Table 1. continued

Noise Signal	Increasing the noise level, which leads to the decrease of the signal to noise ratio (S/N), causes degradation of the bandwidth and roll-back of the transmission rates. In severe cases it can lead to DoS attack.
DoS	Denial of service attack can also impact the media access control (MAC) layer. For this, the attacker does not have to be physically tampering with the infrastructure, though the ability to inject frames directly into the channel is required. A MAC-layer-based DoS attack offers the following advantages to the attackers: - *Medium Independency:* Since many MAC-based communication protocols (i.e., 802.11) have similar MAC layer structures, a single MAC-layer attack can devastate many different infrastructures. - *Energy Efficiency:* A MAC layer attack does not necessarily and directly deal with the weakening of the communication signals, therefore these types of attacks require less amount of energy compared to the physical layer attacks
Jamming	Jamming happens when the communication channel is flooded with MAC layer queries. In this scenario, the MAC layer will not be able to service legitimate queries. Jamming can be considered as a DoS attack at MAC layer.
Blackhole Attack	In this type of attack, the attacker (or a malicious node) advertises a zero routing metric for all destinations. This causes all the neighbor nodes to route all their packets through the attacker (node). This can also be recognized as a DoS attack at the network layer**.**
Wormhole Attack	In this attack, the attacker records packets at one location in the network and tunnels them to another location in the network. This can cause an abrupt of service (DoS) due to the invalidity of routes for the packets, which are routed through this tunnel.
Byzantine Attack	This type of attack incorporates more than one attacker (malicious adversaries). A Byzantine attack involves the leaking of authentication/authorization secrets so that the malicious adversaries are indistinguishable from legitimate nodes. Therefore when adversaries are accepted in the communication schemes, they can cause various types of malicious activities, such as route changes, route loops, and nonoptimal routes. Byzantine attacks are very difficult to be identified.
Information Disclosure	In this scenario, a compromised node may leak confidential and vital information to unauthorized nodes in the network, such as, geographic location of nodes (sender, receiver, and intermediate nodes), network topology, and optimal routes.
Resource Consumption Attack	This type of attack can be discussed as a physical layer issue or a network layer issue. In the network layer, this type of attack directly deals with routing issues rather then energy related issues. Therefore, a malicious node tries to consume and waste the resources in the network through network layer-related activities, such as, unnecessary requests for routes, very frequent beacon packet creations, initiating a lot of route discoveries, and forwarding of staled packets to nodes.
Routing Attacks	These types of attacks deal with the routing algorithms and procedures, such as, routing table overflow and poisoning, packet replication, route cache poisoning, and rushing attack. These are further discussed more in the fifth section.
Others	Other types of network layer attacks include attacks on IP header/address (address sweep scan, timestamp attack, source route attack, record route attack, and fragment DoS attack) and internet control message protocol (ICMP) floods.
Attacks on TCP	Attacks on the transport control protocol (TCP) include acknowledgement (ACK) DoS, synchronization (SYN) flood, LAND attack (where spoofed TCP SYN is sent) "sending a spoofed TCP/SYN packet," session and tear-down attacks, session hijacking, and port-scan attack.
Attacks on UDP	Attacks on user datagram protocol (UDP) include port attack, (UDP flooding) and session hijacking (using a valid session ID).
Session, Presentation, Application	Higher layers (session, presentation, and application layers) are more specific and application oriented. Therefore these types of attacks vary in different networks and applications.

to the OSI layered model, namely, physical, MAC, network, transport, session, presentation, and application layers. Internet-based systems have adopted a more simplified five-layer approach based on transport control protocol (TCP)/IP protocol stack suite, in which the top three layers of the seven-layer model (session, presentation, and application layers) have been merged as a single layer: the TCP/IP application layer (see Figure 2) (Adibi, Erfani, & Harbi, 2006; Lu, 2002; Manoj & Murthy, 2005).

Wireless Routing Protocols in General

Ad hoc routing protocols are divided into the following categories:

Proactive (Table-driven)

In these types of routing protocols, nodes constantly search for routing information and storing them in tables, therefore when a route is needed, the route is already known. The major disadvantages of proactive routing protocols are:

- Consumption of relatively more bandwidth compared to identical amount of data transfer in other routing schemes.
- Increase of traffic overhead due to the constant updates.

The advantage is that there is no delay in route and destination determination. Examples of proactive routing protocols are (Lang, 2003):

- DSDV (destination-sequenced distance vector routing)
- OLSR (optimized link state routing)

Reactive (On-demand)

In reactive protocols, routes are determined as they are needed through "*route request (RREQ)*" and "*route reply (RREP)*" inquiries. The advantage of a reactive routing protocol is the fact that it requires relatively fewer traffic overhead. The disadvantage of reactive routing protocols, however, is relatively longer delays due to the sending and receiving RREQs and RREPs. Examples of reactive routing protocols are (Lang, 2003):

Figure 2. OSI Model vs. TCP/IP protocol stack

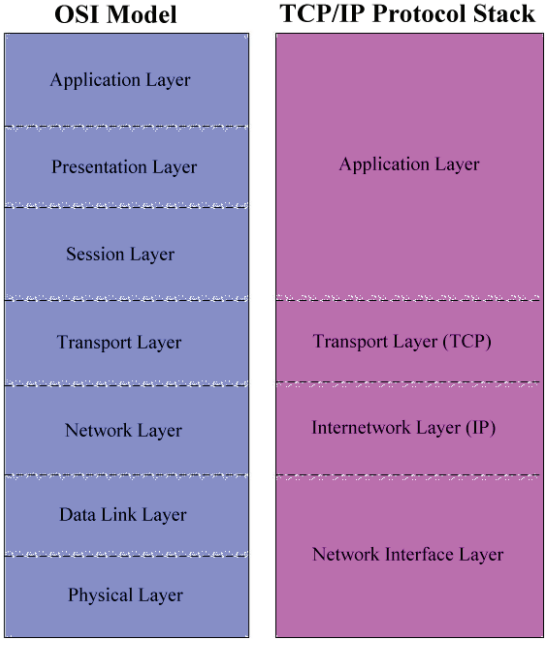
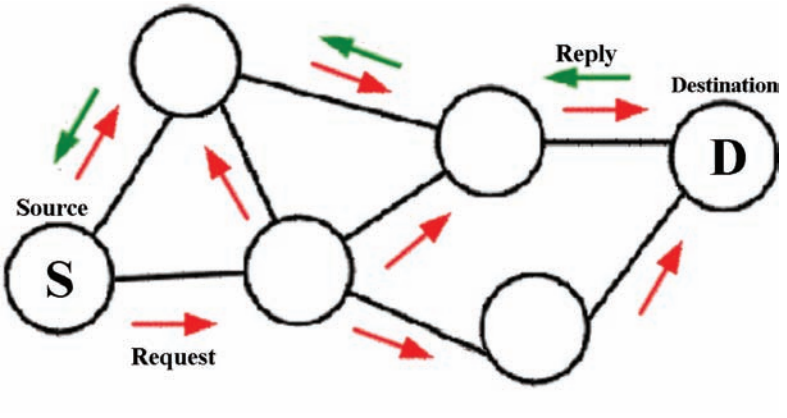


Figure 3. RREQ and RREP inquiries in reactive routing protocols



•DSR (dynamic source routing)
•AODV (ad hoc on-demand distance vector routing)

Besides reactive and proactive schemes, other types of routing protocols include (Lang, 2003):

- **Hybrid (pro-active/reactive):** A blend of reactive and proactive schemes, such as, *zone routing protocol (ZRP).*
- **Hierarchical:** Topology is divided into several local regions and local traffic is handled locally, such as, *hierarchical state routing protocol (HSR).*
- **Geographical:** These protocols use geographical coordinates in locating routing information, such as, *location-aided routing (LAR).*
- **Power aware:** In these protocols, power consumption is a serious factor, such as (Maleki, Dantu, & Pedram, 2002), *power-aware source routing (PSR).*
- **Multicast:** Multicasting is the transmission of data to groups of mobile-hosts identified by a single destination address, such as, *multicast ad hoc on-demand distance vector (MAODV).*

MANET SECURITY REQUIREMENTS

Ad hoc networks require relatively stronger security measures due to the nature of their topological weaknesses. The fact that there is no central infrastructure for ad hoc entities requires that every individual ad hoc element be part of the broader security scheme. Other issues also play roles, such as limited energy (relatively low battery life) and lack of physical security (i.e., the device could be stolen or tampered with). To remedy these limitations, it is necessary to establish cooperation enforcement between all entities and utilize secure routing schemes and efficient key management. The last two issues are discussed in this chapter in more details.

Secure Routing

The objective of secure routing is to provide a means for authenticating routing decisions and ensuring information integrity. The entity authentication includes authentication of source, destination, and all of the intermediate nodes. For specific ad hoc routing protocols, different measures, such as asymmetric or symmetric key cryptography, could be used.

ATTACKS ON AD HOC ROUTING PROTOCOLS

Attacks on ad hoc routing protocols are presented in Figure 4 and Table 2. Again these attacks are categorized into passive and active attacks. Each attack works in such a way as to paralyze a section of the routing protocol, therefore securing the routing protocols is very important.

In order to prevent attacks on routing protocols, security measures should be taken into consideration to prevent attacks and fortify the routing algorithms. These measures should provide the followings:

- **Availability:** Ultimately it should always be possible (with very high probability) to find an available route from any source to any destination within the wireless range. In ad hoc routing protocols, this feature should include preventing routing table overflow (an entry in the table to a nonexisting destination) and rushing attacks (an attacker disseminates RREQs quickly throughout the networks, suppressing any later legitimate RREQs when nodes drop them due to the duplicate suppression).
- **Isolation:** Ability to identify misbehaving nodes and disable them from interfering with the routing schemes. Preventing wormhole and black hole are examples of this category.
- **Lightweight computations:** Assigning heavy computing tasks to the least possible number of nodes (battery power protection) to prevent sleep deprivation.
- **Location privacy:** Protecting information about the location of nodes in a network and the network structure, to prevent location disclosure.
- **Self-Stabilization** – Automatically recover from any problem in a finite amount of time without human intervention.
- **Byzantine robustness:** This requires the function of the routing protocol to work correctly even if some of the nodes participating in routing are intentionally disrupting its operation. This is important in preventing impersonation attacks.

Figure 4. Active and passive attacks in ad hoc routing protocols (Adapted from Wang, Lu, & Bhargava, 2003)

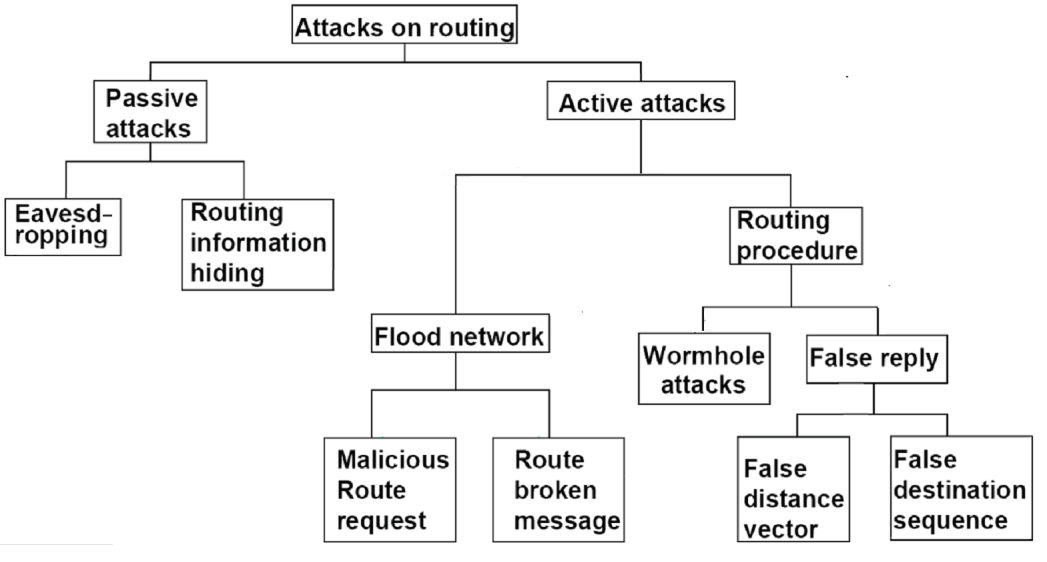


Table 2. Definition to a few of attacks for ad hoc routing protocols

Route Broken Message	Sets false route error to send a message back to the source (route discovery is reinitiated). This exhausts the limited bandwidth.
Malicious Route Request	Sends an invalid route request. This exhausts the limited bandwidth.
False Distance Vector	This involves replying "one hop to destination" to every request and selecting an enough large sequence number. This is an attack on the connectivity.
False Destination Sequence	This is to select a large number of hop to the destination, which is an attack on the connectivity.
Routing Table Overflow	A malicious node advertises routes to nonexisting nodes. Proactive routing protocols are more vulnerable.
Routing Table Poisoning	A malicious or compromised node sends fictitious routing updates or modifies genuine route updates, which causes suboptimal routing.
Packet Replication	A malicious or compromised node replicates stale packets causing excessive bandwidth consumption.
Route Cache Poisoning	An advisory can poison the route cache, which is a major issue for on-demand routing protocols, since they maintain a route cache to all known nodes.
Rushing Attack	An advisory that received a RREQ from a source floods the network quickly before any other legitimate nodes can react, causing other nodes to believe that they have received duplicates, thus discarding the legitimate responses. Therefore any route discovered by the source node would contain the advisory node information as one of the legitimate intermediate nodes.

Possible Solutions

To offer secure routing protocols, the following solutions are used:

- **Trusted route discovery:** To avoid internal attacks, the route discovery phase in ad hoc routing protocols should send packets via trusted routes.
- **Redundant paths and multipath routing:** Having redundant path increases route robustness by providing more route choices, such as in multipath ad hoc routing protocols.
- **Nondisclosure method and anonymous routing:** Anonymous routing avoids the location disclosure by using distributed independent security agents. This way outsiders could not identify the communicating parties.
- **Hierarchical structure or zone-based routing:** This type of routing protocol provides a foundation for authentication and local link-state routing.
- **Authentication among hosts:** This requires two-way authentication schemes for all parties to prevent impersonation (spoofing).
- **Preventing traffic pattern detection:** This is important in hiding the traffic patterns and frequency of transmitting information, as part of anonymous routing.
- **Intrusion detection:** Monitors the behavior of suspected hosts for anomaly detection and attack prevention.
- **Securing the medium:** To prevent physical-layer-based DoS attack, there has been a few methods introduced as security deterrence schemes, such as:
  - *Frequency inversion*
  - *Frequency hopping*

These two methods will be discussed in details in the next section.

CHALLENGES IN SECURE ROUTING FOR MANETS

As mentioned previously, securing routing protocols for wireless systems is more challenging than

securing wired protocols, because not only do all of the possible wired-based attacks apply to ad hoc networks, but also mobility allows new attacks. The most important difference is the vulnerability of the medium. This is very important because everyone shares the same medium (open air) and if extra attention is not giving to its security, it could contribute to a DoS attack (lack of availability or jamming). Therefore the followings are the extra challenges for securing wireless routing protocols:

- **Intrusion detection:** Intrusion detection attempts to detect any malicious or unauthorized activity, either caused by an internal entity or an external source. There are a few types of intrusion detection systems:
  - *Anomaly-based* : Compares the activities in a network with a predefined normal activity map. In these systems, a sudden change in the activities would trigger anomaly alarm detection. Other types include: *network intrusion detection system (NIDS), host-based intrusion detection system (HIDS), application protocol-based intrusion detection system (APIDS),* and *protocol-based intrusion detection system (PIDS).*
- **Secure routing:** This shares a common ground with a layered approach, in a sense that security mechanisms have been integrated with the normal routing procedures. Routing is mostly covered in the network layer. Therefore secure routing is provisioned in the network layer. Secure routing will be discussed in details later in this chapter
- **Key management service:** Because of the difficulties in key exchange, the key management is a challenge in ad hoc networks. The following schemes are a few examples of existing key exchange methods ("Key Management," 2001):
  - Signature keys
  - Signature verification keys
  - Authentication (public, private, secret) keys
  - Data encryption (long-term, short-term) keys
  - Keys based on random number generation
  - Key encryption keys, which are further used for wrapping keys
  - Derivation keys used from master keys and master keys used from derivation keys
  - Key transport for public and private keys
  - Static key agreement used for public and private keys
  - Ephemeral key agreement for public and private keys

Key management faces the following particular challenges:

- Lack of a security infrastructure
- Limited processing power
- It should be fully distributed with minimal dependencies
- Domain parameter and public key validations
- Keys and related material compromise
- Key recovery: consideration and policy
- Audit and accountability issues

Therefore the challenges are trust model, cryptosystems, key creation, key storage, and key distribution.

- **Securing the medium:** To prevent DoS, the following techniques are used as security deterrents:
  - *Frequency inversion*: The process of altering the signal's frequency spectrum in such a way that the signal could not be reconstructed and understandable without the knowledge of the inversion pattern.
  - *Frequency hopping*: Dividing the spectrum into various frequencies and using different frequencies in a predetermined fashion.
  - *Shared secret frequency key*: Sharing the secret of frequency-pattern between transmitters.

KEY MANAGEMENT APPROACHES

Due to the variable nature of ad hoc network topologies and the physical and resource limitations, key management is of great importance. There are many proposals for the key management for ad hoc protocols, however we introduce two methods, namely, *ad hoc key distribution center (AKDC)*, and *decentralized key generation and distribution (DKGD)* (Adibi et al., 2006):

- **Ad hoc key distribution center:** As shown in Figure 5, AKDC uses a centralized ad hoc scheme for key management, distribution, and access. In the AKDC, each device wishing to communicate with another device will have to undergo the following series of processes by the AKDC:
  - Identity and location determination
  - Authentication
  - Authorization
  - Key provision
  - Key delivery

  A lot of intelligence and power must be integrated into the design of an AKDC, however, there are a few downsides of having a central point. The fact that there is a known center for key distribution and its location is known to all, makes the AKDC prone to a variety of attacks, including DoS attack. This problem is remedied by the use of a decentralized and distributed scheme.
- **Decentralized key generation and distribution:** In a DKGD scheme (Figure 6), the key management scheme is distributed across the wireless range through DKGD agents. Every ad hoc element discovers the closest DKGD agent and binds with it. The fact that DKGDs are distributed across the network poses less of a security concern as the single point of failure is no longer an issue. No matter if AKDC or DKGD is used, all legitimate local ad hoc elements should register with the AKDC or the DKGD.
- **Ad hoc gateway access control (AGAC):** So far, the AKDC and DKGD schemes assume in-domain communications among ad hoc elements. However for inter-domain security measures when an outside element seeks communication to a local element, a new element, which is called the AGAC, is responsible for the security concerns. AGAC

Figure 5. AKDC scheme (Adapted from Adibi et al., 2006)

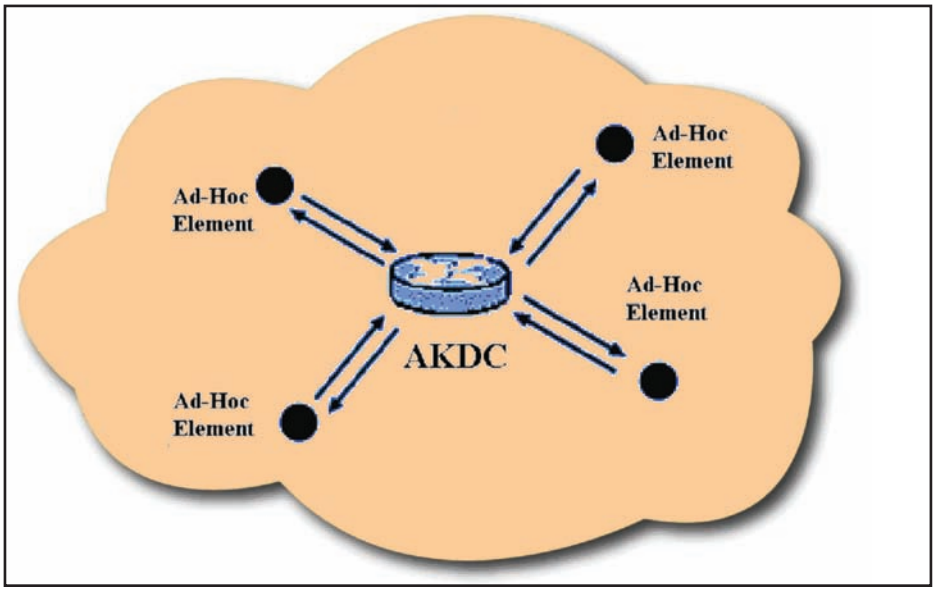


Figure 6. DKGD scheme (Adapted from Adibi, Erfani, & Harbi, 2006)

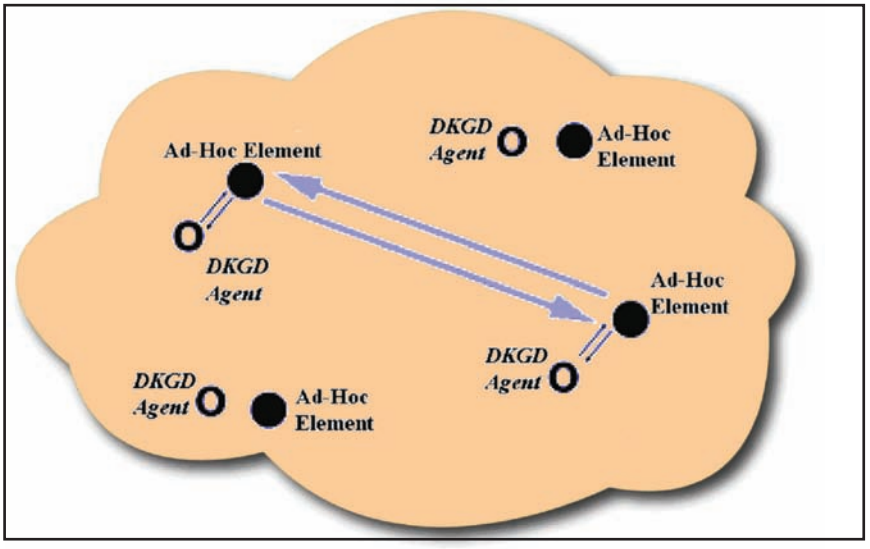
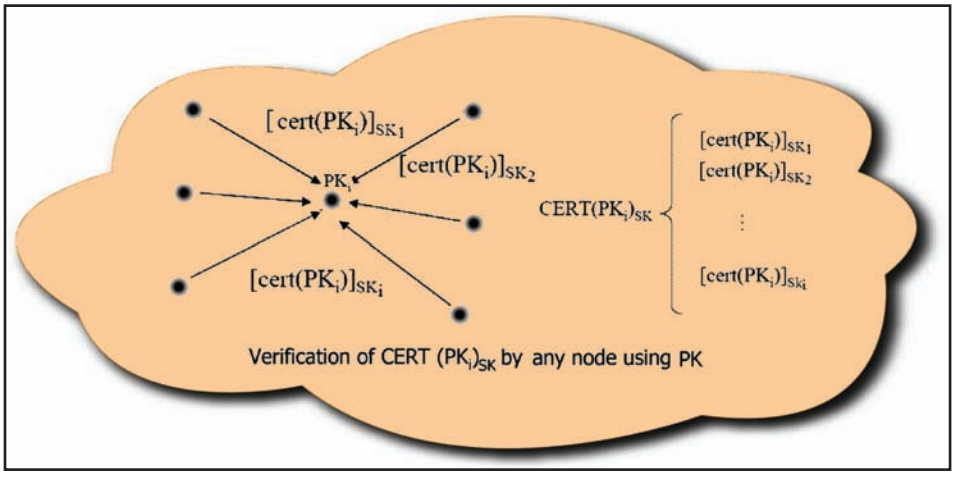


Figure 7: Self-organized certificate authorities (SOCA) (Adapted from Michiardi, 2004)



agents are located at the boundaries of radio domains, that is, where two or more local ad hoc domains intersect.

- **Secure and efficient key management (SEKM):** SEKM (Wu, Wu, Fernandez, Ilyas, & Magliveras, 2005) creates a public key infrastructure (PKI) using a secret shared key scheme and on top of an underlying multicast server groups. In SEKM, a view of the certificate authority (CA) is created by each server group. This provides and update for certificate services for all the participating nodes. For an efficient certificate delivery service, a ticket mechanism is introduced and used.
- **Self-organized CA (SOCA) (Michiardi, 2004):** In traditional cryptographic systems, there is one sender, one receiver, and an eavesdropper who is the opponent. However a SOCA is based on threshold cryptography.

Threshold cryptography allows one to share the power of a cryptosystem in which the power to regenerate a secret key is shared among several agents (Figure 7). The advantage of this is the distributed approach with self-organization. The downside is the network density.

SECURITY MECHANISMS IN MANETS

There are several mechanisms, which are embedded into the protocol schemes, which contribute to the robustness of security. Below is a list of a few of these mechanisms.

- **Multipath routing:** Multipath routing (Bonum & Othman, 2003) works by enhancing data confidentiality through the transmission of data via multiple paths. This is done to prevent any fixed unauthorized nodes from attaining useful data. This requires no encryption as data is already "split" among various paths.
- **Hierarchical routing:** Hierarchical routing (Rhee, Park, & Tsudik, 2004) is one of the categories of ad hoc routing protocols in which traffic handling is done through different layers and local activities are kept local. Therefore there is no need to broadcast all changes to the entire radio domain. Only global moves are reported across the entire network. In the security and key management cases, the architecture could use a two or more layered key management approach where groups of nodes are divided into *cell groups* consisting of ground nodes and *control groups* containing cell group managers.
- **Tunneling:** Tunneling (Choi, Song, Cao, & Porta, 2005) is widely used in many security schemes, such as virtual private networks (VPNs) and IP-Security (IPSec).
- **Other Measures in MANETs:** Other measures, which could be adopted in ad hoc scenarios are (Menezes, Oorschot, & Vanstone, 1996):
  - *Web of trust (PGP)*: Which is a Peer-based (one-to-one) system and requires no Certificate Authority. PGP symmetric and public-key cryptography schemes and includes a mechanism, which binds the public keys to the user identities.
  - *Crypto-based ID:* A crypto-based ID (CBID) requires no infrastructure and uses a binding between address and signature.
  - *ID-based crypto*: The ID-based crypto suggests that having an identity implies being authorized, therefore no certificates are needed.
  - *Context-dependent authentication*: Authentication is based on the content of the message.
  - *Password authenticated key exchange (PAKE):* In a PAKE, two or more communication parties, based on their knowledge of a password only, establish a cryptographic key through a message exchange, in such a way that an unauthorized entity cannot participate in the scheme and is kept from guessing the password. There are two forms of PAKE, which are balanced and augmented schemes.
  - *Cooperation Enforcement Mechanisms using Game Theoretical Approaches:* Game theory is a powerful tool that models interactions among participating entities. Each player tries to maximize some utility function in a distributed manner. Nash equilibrium is where the games settle, assuming the equilibrium exists, however, since nodes usually act selfishly, the equilibrium point might not be the optimal social point.

SECURE PROTOCOLS FOR MANETS

The main idea for these protocols is to offer extended security, therefore with only security in

mind, the entire protocol functionalities have been designed for security in the the network layer. Four of these protocols are introduced as follow:

ARIADNE (A Secure On-Demand Routing Protocol for Ad Hoc Networks)

ARIADNE (Hu, Perrig, & Johnson, 2002) relies only on highly efficient symmetric cryptographic systems and does not require a trusted hardware or powerful processors. Routing messages can be authenticated using ARIADNE through one of the following three schemes: 1) Using shared secrets among each pair of nodes, 2) Using shared secrets among communicating nodes together with broadcast authentication, and 3) Using digital signatures. ARIADNE works well with timed efficient stream loss-tolerant authentication (TESLA) (Hu et al. 2002), which is an efficient broadcast authentication scheme that requires loose time synchronization, where a receiver knows an upper bound of difference between sender's local time and the receiver's local time.

SEAD (Secure Efficient Distance Vector Routing for Mobile Wireless Ad Hoc Networks)

SEAD (Hu, Johnson, & Perrig, 2002) is based on the design of the destination-sequenced distance-vector routing protocol (DSDV). To prevent DoS, SEAD uses efficient one-way hash functions and does not include the usage of asymmetric cryptographic operations. SEAD is robust against multiple uncoordinated attackers, which creates incorrect routing state for other nodes.

SADSR (Security-Aware Adaptive Dynamic Source Routing Protocol)

SADSR (Ghazizadeh, Ilghami, Sirin, & Yaman, 2002) includes an authentication scheme in which, the routing protocol messages are authenticated using asymmetric cryptographic-based digital signatures.The basic idea behind the functionality of SADSR is to have multiple routes to every destination and to store a local trust value related to each node throughout the network. A trust value is also assigned to each path based on nodes trust values. The paths with higher trust values are preferred and selected for routing.

SDSR (Secure Dynamic Source Routing)

SDSR (Kargl, Geiss, Schlott, & Weber, 2005) prevents various potential (active and passive) attacks to the ad-hoc-based networks. It also deals with selfish nodes in the following scenarios:

- *Motivation-based approaches*: Try to motivate network users to actively participate in the MANET.
- *Detect and exclude*: This scheme detects and excludes selfish nodes from the routing scheme
- *Mobile Intrusion Detection System (MobIDS)*: Focuses on integrating with other mechanisms for detecting selfish nodes.

CONCLUSION

Attacks can be categorized as per node behaviors, protocol schemes, or layered approaches. Security challenges in MANETs include securing the medium (preventing from DoS attack, etc.), securing the routing schemes, intrusion detection and prevention, key management, peer-to-peer security options, user and data authentication/authorization, data encryption, and digital signatures.

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KEY TERMS

Access Control: This is a security mechanism to make sure that only legitimate parties have access to the data they are supposed to have access.

AKDC: Ad hoc key distribution center is a central component in an ad hoc network responsible for providing keys to ad hoc elements.

ARIADNE: A secure on-demand routing protocol for ad hoc networks.

Authentication: Authentication is required to make sure communicating parties are the ones who they claim to be.

Availability: A stochastic measure of predicting the availability of the communication channel and resources to the users

CA: Certificate authority is responsible for issuing digital certificates.

Confidentiality: This is a basic security requirement in which the address, location, and/or the data transferring between two communicating parties are to be kept as secrets.

DKGD: Decentralize key generation and distribution is another key distribution scheme for ad hoc networks in which the key distribution mechanism is done by distributed elements, not by a centralized entity.

Integrity: This is another basic security requirement. Integrity guarantees the correctness of the data transferring between two communicating parties, or their location information.

Nonrepudiation: This is a concept of ensuring that none of the communicating parties can deny the fact that they had sent or received certain data.

SADSR: Security-aware adaptive dynamic source routing protocol.

SEAD: Secure efficient distance vector routing for mobile wireless ad hoc networks.

SEKM: Secure and efficient key management is another key management scheme in which involves public key infrastructure.

SDSR: Secure dynamic source routing.

SOCA: Self-organized CA is a threshold-based cryptosystem in which the power is shared among different CAs.

Chapter XXXII
A Novel Secure Video Surveillance System Over Wireless Ad Hoc Networks

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ABSTRACT

The integration of wireless communication and embedded video systems is a demanding and interesting topic which has attracted significant research efforts from the community of telecommunication. This chapter discusses the challenging issues in wireless video surveillance and presents the detailed design for a novel highly-secure video surveillance system over ad hoc wireless networks. To this end, we explore the state-of-the-art cross domains of wireless communication, video processing, embedded systems, and security. Moreover, a new media-dependent video encryption scheme, including a reliable data embedding technique and real-time video encryption algorithm, is proposed and implemented to enable the system to work properly and efficiently in an open and insecure wireless environment. Extensive experiments are conducted to demonstrate the advantages of the new systems, including high security guarantee and robustness. The chapter would serve as a good reference for solving the challenging issues in wireless multimedia and bring new insights on the interaction of different technologies within the cross application domain.

INTRODUCTION

With the ever-increasing security demands of military and scientific applications, the development of a highly secure and reliable video surveillance system attracts significant interests from both academia and industry. The implementation and efficiency of such a system are greatly affected

by the techniques in wireless communication, video processing, embedded systems, and security guarantee.

Recent advances in embedded system and wireless communications are enabling cost-effective digital wireless multimedia systems. The forthcoming integration of wireless communications and embedded video systems is a demanding and interesting research topic. Video surveillance has resorted to wireless transmission due to the several serious problems when the traditional coaxial or high-tech fiber-optic cables are adopted to transmit video images from the surveillance cameras to the stations at which the images are monitored and/or recorded. Compared with the traditional wire-line counterparts, wireless video surveillance systems do not require expensive and time-consuming system constructions and civil-engineering work. They can therefore be deployed rapidly with negligible environmental impact. Furthermore, wireless systems generally require lower costs of network maintenance, management, and operation.

However, some fundamental issues, such as framework design of wireless networks, video processing, video data transmission, video quality control, and system security should be resolved before wireless video surveillance systems can be successfully deployed (Garcia-Macias et al, 2003). Among these important issues, the system security is the most challenging problem that becomes the main concern of this chapter. Intel IXP425 network processor provides an ideal choice for implementing secure ad hoc video surveillance system, but the security issue is still a hot-spot that IXP425 cannot handle well. Therefore, an effective video encryption algorithm is necessary and meaningful in a wireless video surveillance system. At the same time, the secure routing protocol and system architecture should be carefully designed to avoid serious security flaws (Yin, Lin, Sebastien, & Chu, 2005).

This chapter explores the state-of-the-art cross domains of wireless communication, video processing, embedded systems and security, discusses the challenging issues in wireless video surveillance, and presents the detailed design of a novel highly-secure video surveillance system over ad hoc wireless networks. The rest of this chapter is organized as follows. Section 2 provides a review of wireless networks, ad hoc solution and security issues. Section 3 presents the design and implementation for the new video surveillance system and Section 4 evaluates its performance. Section 5 highlights the future trends in the relevant research areas. Finally, Section 6 concludes this chapter.

BACKGROUND

Wireless Networks

Wireless technologies, in the simplest sense, enable one or more devices to communicate without physical connections (without requiring peripheral cabling). Wireless networks serve as the transport mechanism among mobile devices or between these devices and the fixed wired networks (e.g., enterprise networks and the Internet). A wireless network has tremendous advantages in comparison with its wired counterpart: no network cable has to be installed through walls and floors, thus greatly reducing the cost and making the architecture more flexible.

The development of 802.11g (IEEE, 2003) based on the orthogonal frequency-division multiplexing (OFDM) technology allows high-load applications to be adapted in wireless environment. It is claimed that an optimal throughput of 54Mps and a range up to 100 feet indoors can be achieved. As the signal is modulated at 2.4 GHz, it is less affected by walls and physical obstacles than 802.11a (5 GHz). Thus our system is based on the 802.11g wireless infrastructure ad hoc networks.

Ad Hoc Solution

Ad hoc networks are a new wireless networking paradigm for mobile hosts. Unlike traditional mobile wireless networks, ad hoc networks do not rely on any fixed infrastructure. Instead, hosts rely on each other to keep the network connected. Ad hoc networks are designed to dynamically connect remote devices such as cell phones, laptops, and PDAs. These networks are termed "ad hoc" because

of their shifting network topologies. Whereas wireless LANs use a fixed network infrastructure, ad hoc networks maintain random configurations, relying on a master-slave system connected by wireless medium to enable communication between mobile devices (Haas, 1999; Zhou, 1999).

The system we are designing is organized in an ad hoc manner. The nodes themselves (with camera) are carrying the flux towards the monitoring center, and all the routing tasks are performed by the camera nodes. A careful deployment can share the traffic load among all the camera nodes and effectively reduce the bottleneck effect as compared with an architectural network. It is also the cheapest solution as there is no need of extra networking hardware besides the cameras, network processors, and the monitoring center.

However, the design of ad hoc architecture is complex because of the routing and security issues. In a monitoring system, the node positions are static and predetermined by the topology of the building. The cameras are in a nonprotected environment, and they are susceptible to be damaged or even destroyed. Thus it would be preferable if every node has at least two direct neighbors on the way towards the monitoring center so that the system can still work properly in case some camera nodes are faulty.

Security Issues

Among the issues the wireless solution face, the system security is the most challenging problem. The NIST handbook *An Introduction to Computer Security* generically classifies security threats into nine categories ranging from errors and omissions to threats to personal privacy (Basgall, 1999). All of these represent potential threats in wireless networks as well. However, the more immediate concerns for wireless communications are device theft, denial-of-service, malicious hackers, malicious code, theft of service, and industrial and foreign espionage.

Data embedding techniques allow for a signal to be hidden without dramatically distorting the original content. Effective data embedding techniques should be able to invisibly embed data, allow for easy extraction, and achieve a high embedding rate. The most popular application of data embedding is digital watermark. Lots of research work has been done in this field over the past years. Although it is worthy noting that none of the existing schemes are capable of satisfying the demand for media-dependent access control in wireless video surveillance system, some ideas and framework of these digital watermark algorithms are valuable and may be extended to design the desired data embedding scheme (Yin, Lin, Qiu, Min, & Chu, in press).

The classical approach to watermark compressed video stream is to decompress the video, then use a spatial-domain or transform-domain watermarking technique to embed the watermark into the video signal, and finally recompress the watermarked video. Alattar, Lin, and Celik (2003) point out three major disadvantages of using the classical approach and further present a faster and more flexible approach to watermark compressed video named as compressed-domain watermarking. With this approach, the original compressed video is partially decoded to expose the syntactic elements of the compressed bitstream (such as encoded discrete cosine transform [DCT] coefficients) that is modified to insert the watermark and reassembled to form the compressed watermarked video.

Patchwork (Bender, Gruhl, Morimoto, & Lu, 1996) and quantization index modulation (QIM) (Chen & Wornell, 2001) are the two known techniques for the embedding algorithm. Patchwork (Bender et al., 1996) is a statistical scheme based on a pseudorandom and statistical process. Patchwork is host image independent and can invisibly embed a specific statistic pattern (composed of several pairs of specific pixels) in a host image with a Gaussian distribution. It shows reasonably high resistance to most nongeometric image modifications. But the major disadvantage is that only one bit can be embedded in one frame. Moreover, this algorithm operates specific pairs of points and the structure of video bitstream is changed by some adaptive processes such as transcoding. So during the detecting procedure these pairs of points at the same position are not the same as the original, or even

out of borders due to the change of image size. As a result, the extracted data are likely to be wrong. Our proposed scheme is based on the statistical property of the luminance value, but differently we use image fields instead of pairs of points to overcome above mentioned problems.

Chen and Womell (2001) propose a QIM scheme for efficiently embedding and drawing out data. QIM method embeds information not simply by adding numbers to the host signal, but by first modulating an index of sequence of indices with the embedded information and then quantizing the host signal with the associated quantizer or sequence of quantizers. During the detecting procedure, the embedded information is determined by judging the minimum distance between the embedded signal and different quantized results. It is known that the QIM method is better than additive spread spectrum and generalized low-bits modulation (LBM) not only from the point of rate distortion-robustness tradeoffs, but also against bounded perturbation and fully informed attacks arising in several copyright applications. Since requantization is carried out in the transcoding procedure and the quantizers are different from the ones used in video encoding process, lots of computational errors are produced and the detection is likely failed. Our scheme improves the QIM by proposing an approach to alter the average luminance value of fields.

Routing Protocol

In recent years, a large number of ad hoc routing protocols have been proposed in the literature (Broch, Maltz, Johnson, Hu, & Jetcheva, 1998; Perkins & Royer, 1999; Per, 1999; Samir, Perkins, & Royer, 2000). In all these studies, two on-demand routing protocols show good performance: ad hoc distance vector (AODV) (Perkins & Royer, 1999) and DSR. In a scenario where a high volume of traffic goes through a static ad hoc network (by static we mean that the nodes configuration does not change or changes slowly), AODV performs better than DSR due to less additional load being imposed by source routes in data packets. Therefore our system is based on the AODV protocol.

AODV is an on-demand protocol. Each node maintains its routing table only for the routes they actually use to communicate with other nodes. If a node wants to initiate a new communication with another node that is not in its current routing table, a route request (RREQ) is broadcast. If a node receives such a request, it looks up its routing table to find whether there is a path to the destination nodes. If there exists a path, it replies a route reply (RREP); otherwise, it broadcasts the RREQ. If a node receives the same RREQ twice, it simply discards the message. Routes are maintained in the routing table as long as they send packets. If nothing is received after a predefined timeout value, the corresponding route entry is deleted. In case of nodes failure, neighbors on the active path send a special RREP to the source which can start a new path discovery phase. Neighbor's discovery is done either by local broadcasting of HELLO messages or by receiving a broadcast message from a neighbor given that the links between nodes are bidirectional.

Perkins and Royer (1999) try to avoid relying on the underlying MAC-layer protocol, but no solution has been proposed to avoid the overhead created by the HELLO message. In our system the routing protocols are coupled with the address resolution protocol (ARP) protocol as described by Desilva and Das (2000) so that we can avoid broadcasting HELLO messages. In addition, it is preferred to implement the routing protocol at link layer due to the following reasons (Johnson, Maltz, & Broch, 2001):

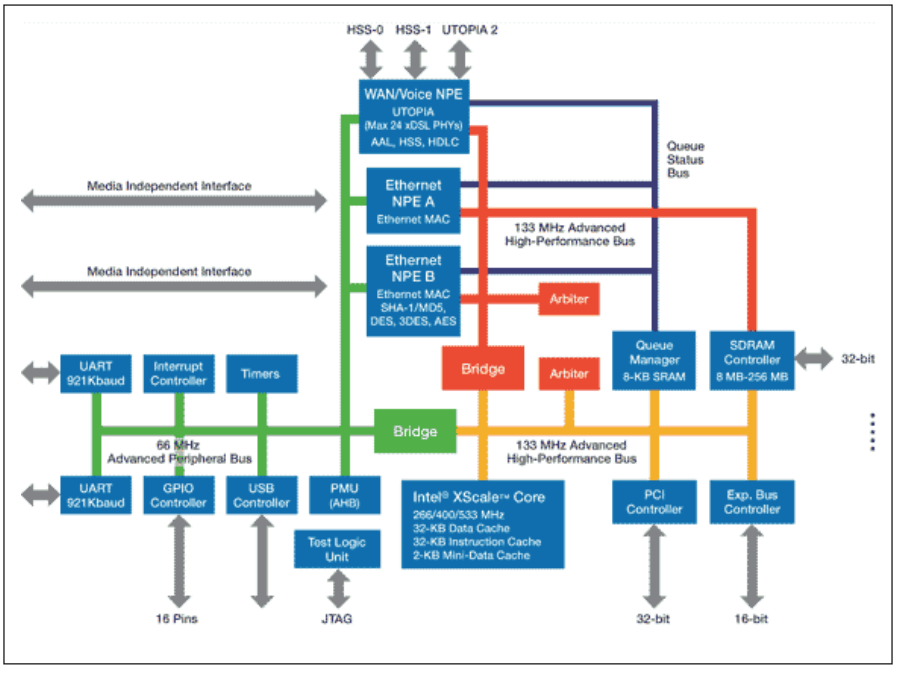
- Pragmatically, running the protocol at the link layer maximizes the number of mobile nodes that can participate in ad hoc networks.
- Historically, the protocol has grew from a multihop propagateing version of the Internet's address resolution protocol (Plummer, 1982), as well as from the routing mechanism used in IEEE 802 source routing bridges (Perlman, 1992).
- Technically, our design would expect the protocol to be simple enough so that it could be implemented directly in the firmware inside wireless network interface cards, well below the layer 3 software within mobile nodes.

Network Processor

The Intel IXP425 network processors are used as the basic processing unit to design our wireless video surveillance system. Intel® IXP425 network processor is a highly integrated, versatile single-chip processor used in a variety of products that need network connectivity and high performance to run their unique software applications. The Intel IXP425 network processor combines integration with support for multiple WAN and LAN technologies in a common architecture designed to meet requirements for high-end gateways, voice over IP (VoIP) applications, wireless access points, small-to-medium enterprise (SME) routers, switches, security devices, Mini-DSLAMs (digital subscriber line access multiplexers), xDSL line cards, industrial control, and networked imaging applications. The framework of Intel® IXP425 is shown in Figure 1 (Intel, 2006). Intel IXP425 network processor provides diverse functionalities, including data encryption, secure data transmission, and multimedia processing, thus making it an ideal choice for implementing secure ad hoc video surveillance systems.

Though Intel IXP425 network processor is an ideal choice for implementing secure ad hoc video surveillance systems, the security issue is still a hot-spot that IXP425 cannot handle well on its own. For example, video encryption is very important in wireless LAN environment since everyone can receive the video content and inject the faked video packets. Unfortunately, normal data encryption functions like AES provided by IXP425 is too computationally expensive to be applied to every single outgoing packet, especially in wireless ad hoc network environment which should consider power limitation of wireless devices (Allman, 2002; Borisov et al., 2003). Therefore, an effective video encryption algorithm is necessary. At the same time, the secure routing protocol and system architecture should all be carefully designed to avoid serious security flaws.

Figure 1. Framework of Intel® IXP425



A NOVEL SECURE VIDEO SURVEILLANCE SYSTEM

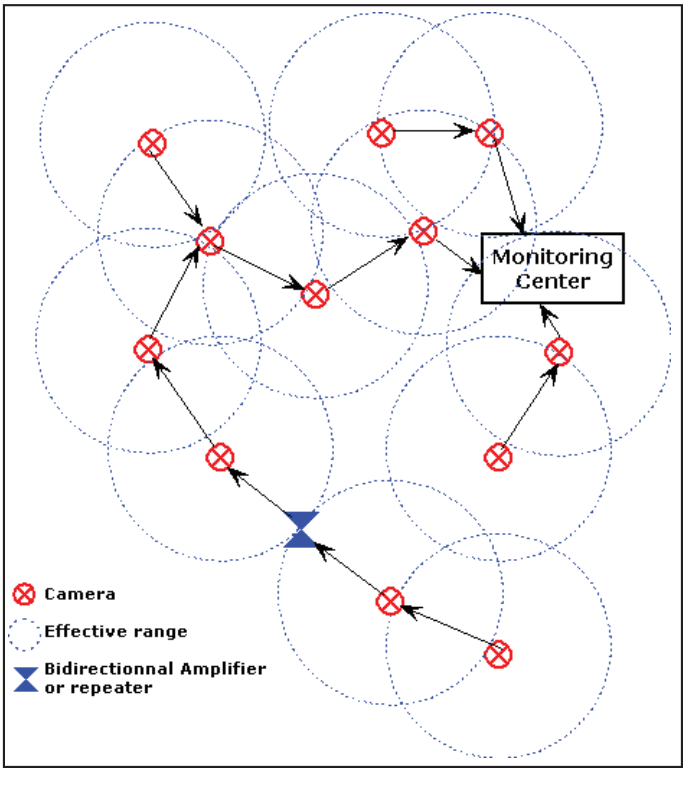
Framework Design of Wireless Networks

The system is based on the 802.11g wireless ad hoc infrastructure. Intel IXP425 network processors are used as the basic processing unit. The 802.11g is a physical layer standard for WLANs with 2.4GHz and 5GHz radio bands. It specifies three available radio channels. The maximum link rate is 54Mbps per channel whereas 802.11b has 11Mbps. The 802.11g standard uses the OFDM modulation. However, for backward compatibility with 802.11b, 802.11g also supports complementary code-keying (CCK) modulation and, as an option for faster link rates, it allows packet binary convolutional coding (PBCC) modulation (Wentink, 2003).

Our wireless video system is composed of a set of camera nodes and a monitoring center, as shown in Figure 2. Each camera node is equipped with an IXP425 processor and 802.11g wireless card. The video source is captured by the camera, and then compressed by the processor locally. After that, a watermark containing the authentication information and encryption key of the video data is embedded into the video signal. The watermark is designed to be robust and difficult for the attacker to remove. The video data are then encrypted using our early proposed video selective encryption scheme (Yin, Lin, Qiu, Li, & Tan, 2005), which is implemented to be compatible with the hardware encryption engine supported by IXP425, so that the whole video processing can be performed in real-time.

The camera nodes are organized as a wireless ad hoc network in which every node also functions as a router to relay the video data from other nodes. Encrypted frames are finally routed to the monitoring center, traveling through a series of camera nodes. Usually the physical locations of all camera

Figure 2. Architecture of secure wireless video systems



nodes are fixed. It is possible that some nodes are out of range from the main network. In this case, some bidirectional signal repeaters or amplifiers could be placed in strategic points to provide robust coverage for every node (Yin et al., 2005).

Video Processing

For the sake of security concerns, encryption keys are updated periodically. Thus, a core part of the system is how to embed encryption keys in the video data stream. Unlike normal watermarking techniques, in our system the camera nodes should not only detect the existence of a new encryption key but also extract it without losing any information, as shown in Figure 3.

Our key embedding algorithm focuses on the reliability and accuracy of embedded keys against the influences introduced by transmission errors and adaptive mechanisms. Real-time processing is also a requirement when designing the algorithm. The key embedding process can be divided into two parts: key embedding and key detecting. The first part is conducted by the video encoder, while the second part is conducted by the video decoder. New keys are embedded in the I-frames (Intra frame) of a group of pictures (GOP) and directly modulated into the direct current (DC) component of DCT coefficients of luminance blocks. In our algorithm, 200 bits of data can be embedded in one I-frame of size 640x480. Moreover, the key takes only 128 bits among the data.

In order to improve the error resilience capability, we employ Reed-Solomon (RS) code as the error control scheme. RS code is used to encode the key messages and an 8-bit flag and this takes the remainder 64 bits for RS code words. Then, all the GOPs are encrypted by the selective encryption algorithm, which contains some hash functions supported by IXP425 hardware, corresponding to the old key. Finally, the encrypted data are sent out to a neighbor node via the wireless network. After the data are received, the incoming packets are first decrypted and then decoded. When the embedded key messages are detected, the new key is used for future data decryption. If a GOP is badly damaged, the embedded key messages may not be extracted correctly. Therefore, we use more than one GOP to embed the rekey messages for redundant recovery (Yin et al., 2005). Figure 4 gives an example of three GOPs containing the redundant key messages.

Figure 3. Real-time key embedding and key detecting process, K_i is the 128-bit key information used to encrypt the video content

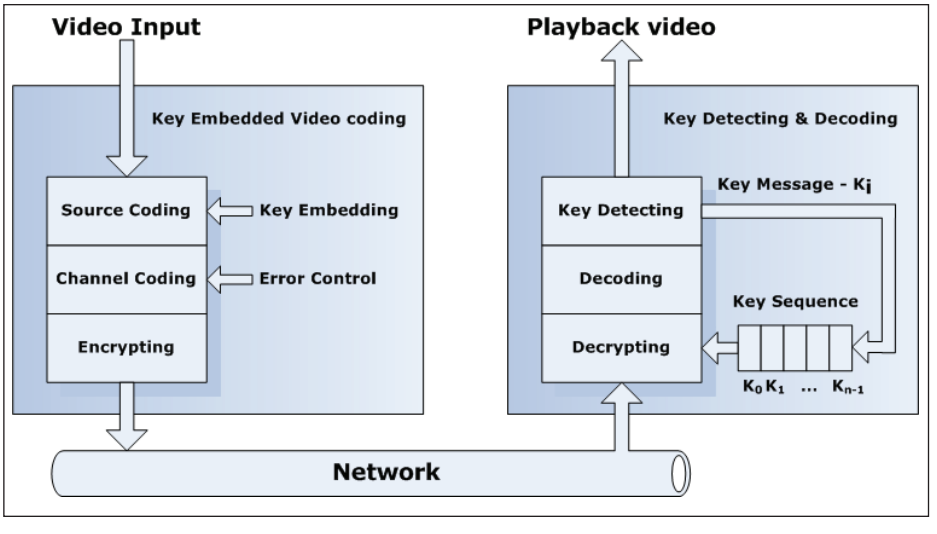
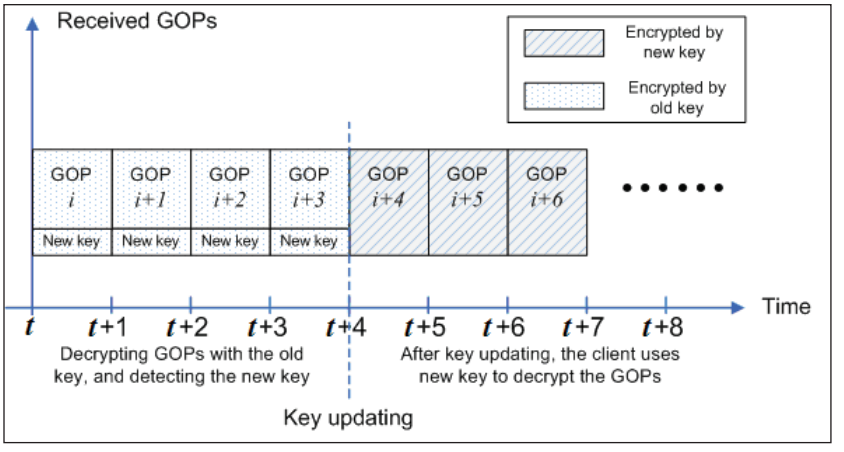


Figure 4. The redundant GOPs used in key updating process. From GOP_{i+1} to GOP_{i+3} there are three GOPs that contain the redundant key messages



System Security Management

To develop a secure wireless video surveillance system, it is necessary to develop an effective video encryption algorithm, and meanwhile the secure routing protocol and system architecture should all be carefully designed to avoid serious security flaws.

Confidentiality

Data confidentiality is usually assured by encryption. However, encryption introduces large computational overhead. In stringent environment like real-time video transmission, encryption can become the system bottleneck and it is the common knowledge that full video stream encryption is not a good choice (Liu & Eskicioglu, 2003). Our video selective encryption algorithm takes advantage of the properties of monitored video to achieve secure, real-time encryption.

If the routing messages are not protected, eavesdroppers may discover the network topology by listening to the routing information and then attack the most active notes in the network. Topology information disclosure is not a threat by itself, but it can make other attacks more efficient. However, encrypting routing information could greatly increase the overhead. The basic AODV protocol has built in capabilities for extension headers. The secure ad hoc distance vector (SAODV) protocol is a proposal by Zapata (2005) for such extension headers. The extensions are used to send signatures and hash values that are later used for verification of the routing packets. The SAODV is not meant to yield any confidentiality since this is usually not needed or desired in general ad hoc networks. The protocol does provide means to get authentication, integrity, and nonrepudiation of the routing control packets. The protocol extensions use asymmetric cryptography to achieve authentication by signing the data packets with the private key. This allows for the destination node and all intermediate nodes to validate the request. Also, this allows for the nodes to be certain that no one has altered the packets. However, some fields of the packets must change and these are signed as if they were zeroed out. To allow for verification of the hop count field, a one-way hash chain is utilized. The initiator of the route request decides a max hop count, such as 10 or 15. It also generates a random value which is sent as the hash for the first hop count. The value is also hashed the max hop number of times producing a so-called top hash. Each node can verify the hop count by checking that the incoming hash value hashed max hop count minus the current hop count number of times is equal to the top hash. Since the top hash value is not changed, and thus signed,

this provides the means to authenticate even the mutable hop count.

The SAODV extensions allow for two different ways for nodes to reply to a route request. The first way is to only allow the destination to reply. In this way the protocol works as described above. The destination node creates a route reply and signs it using its own secret key. The route reply is sent according to the usual AODV and each intermediate node can verify the reply and discard it if not valid. This approach does not consider the possibility of having intermediate nodes reply directly if they do have a valid route already. To add the ability for route discovery optimization a double signature scheme is devised. For each route request a second signature is added to the packet. This signature is stored in each intermediate node when they set up the reverse route. Later on, when a new route is needed because of node movement between the two peers an intermediate node that still has a route can reply directly by also including the second signature and the original signature (Yin et al., 2005). In addition to this, the actual life time is also sent in the reply which is signed by the intermediate node that sends the reply.

Authentication

The host-to-host authentication between the camera and the monitoring center is achieved by data encryption. But in ad hoc networks, we also have to consider the problem of neighbors' authentication, as nodes are "observing" the external world though the "eyes" of its neighbors. The neighbors must be authenticated before any other communication can be initiated. In a nonauthenticated environment, external nodes can insert themselves in the data path and then collect, disrupt, or corrupt the information using man-in-the-middle or black and grey holes attacks. To reduce the effect of computational power consumption attack, the authentication scheme is performed at link layer. Neighbors' authentication is assured by a certificated-based approach (Stallings, 1999) which provides practical solutions for data integrity, authentication, and nonrepudiation. The practical protocol is presented by Luo, Zerfos, Kong, Lu, and Zhang (2002).

Reactive Protection Scheme

The ad hoc environment is usually considered as physically insecure. For instance, cameras can easily be stolen or corrupted. A corrupted camera node can be used as a Byzantine enemy (Lamport, Shostak, & Pease, 1995) to attack the rest of the network. However, resources in the ad hoc network are limited due to the embedded nature of the nodes; especially computational power is the system bottleneck. In this situation, signing every packet between every node is not realistic for real-time multimedia streaming. Besides, if a malicious entity controls a node, it also controls the authentication keys, and systematic authentication is not useful against this type of attack.

In our system only routing protocol messages are systematically signed and time-stampeded to avoid basic attacks such as erroneous routing packet flooding. To prevent more subtle attacks like grey hole or session hijacking, we use the existing knowledge about the data stream (e.g., continuity, stability, fixed length, etc.) to detect misbehavior in the trusted network. Nodes which have detected misbehaving peers break the routing roads coming from the suspected nodes so that further traffic is ignored until a new (authenticated) road request is broadcasted. The level of intrusion detection capability depends on the computational power. The system would have a misbehaving threshold beyond which the system will cut itself from the rest of the network. The level of the threshold and the way to isolate the node from the network is worth further investigation.

Key Distribution

The key distribution solution proposed by Luo et al. (2002) has been chosen to safely distribute and refresh encryption keys and periodically check integrity of the camera nodes. This protocol is based on the threshold share secret revealed by Shamir (1979) and improves the shares refreshing proposed by Herzberg, Jarecki, Krawczyk, and Yung (1995). The system is based on RSA public key signatures. Each node gets a simple certificate in the form $< v_i, pk_i, T_{sign}, T_{expire} >$ where v_i is the identification

number of the nodes, pk_i is the public key, T_{sign} is the time that the certificate is created, and T_{expire} is the certificate expiration time.

SYSTEM PERFORMANCE EVALUATION

This session will test the performance of the system we designed and meanwhile introduce one approach to evaluate such system, which may be applied to general wireless video surveillance systems.

Testing Environment

The testing procedure involves three steps. First we evaluate the video encoding and encryption algorithms, along with the basic network stack evaluation on a single link. In the second step, we measure the performance of a node for transmitting traffic to other nodes. The third step is a simulation study of a large scale network in order to analyze how the system evolves when the number of cameras increases.

- **Single node capability:** The testbed is composed of an IXP425 network processor and its evaluation board. The network interface of the camera node is a wireless 802.11g compatible network interface. A desktop computer equipped with the same network interface is used to stand for the monitoring center and to test the video decryption and playback.
- **Routing capability:** A set of low cost computers is equipped with wireless network interface and generates traffic towards the tested node. Different physical dispositions are set to test one-hop and multihops routing performance.
- **Scalability:** Large scale experiments are very challenging because they require too many hardware. We plan to use the results obtained from Steps 1 and 2 to build a realistic model of the node and simulate a large scale system.
- **Nodal processor:** Intel IXP425 network processor is chosen as the nodal processor of our system. Intel IXP425 is a member of Intel's IXP4XX product line of network processor, for small-to-medium enterprise, consumer, and other edge network applications. Like Intel's high-end network processors IXP2k series, IXP425 is also a multicore system that employs system-on-chip (SoC) techniques to support multiple WAN and LAN technologies in a highly integrated and versatile architecture. The Intel XScale core at up to 533 MHz provides headroom for customer-defined applications. It also supports a single-instruction stream multiple-data stream (SIMD) coprocessor for multimedia application acceleration. In our system, video encoder and watermark embedding are performed on XScale with optimization towards the SIMD coprocessor. Three network processor engines (NPEs), like a micro-engine of IXP1k, 2k network processors, are designed to complement the Intel XScale core for many computationally intensive data plane operations. These tasks include IP header inspection and modification, packet filtering, packet error checking, checksum computation, and flag insertion and removal. The NPE architecture includes an ALU, self-contained internal data memory, and an extensive list of I/O interfaces, together with hardware acceleration elements. The hardware acceleration elements associated with an NPE targets a set of networking applications. Each hardware acceleration element is designed to increase the speed of a specific networking task that would otherwise take many MIPS to complete by a standalone RISC processor. Among these functions, cryptographic hardware accelerators (SHA-1, MD5, DES, 3DES AES) in NPEB are used in our application for selected video encryption.

Experiments on Key Embedding Algorithm

This subsection focuses on the performance evaluation of the key embedding algorithm in a wireless

environment. The algorithm is implemented on the platform of Intel IXP425 network processor.

We use two MPEG-2 test sequences, dinosaur and live-captured video, which are both encoded at 640x480 size and 20fps using 500 frames. The sequences are selected because of their different characteristic in motion and scene change. Dinosaur contains fast motion and scene change, while live-captured video contains slow motion and fixed scene. Besides, we should face the challenge derived from packet loss and bit error. We test the system in a real wireless network environment. The last module is a key detecting and decoding module, which contains selective encryption algorithm, MPEG-4 decoder, and the key embedding algorithm. They are used to decrypt the bitstream using old session key, and then detect the embedded key messages and decode the compressed video into playback video.

Based on this platform, we conduct a series of experiments to evaluate the system performance (Yin et al., 2005). The source-coding distortion introduced by our key embedding algorithm is illustrated in Figure 5. The video clip is MPEG-2 encoded with different modulation cycle. It is then transcoded and decoded by MPEG-4 decoder. All the four pictures are selected from the playback video. Obviously, the modulation cycle is the most important factor that affects the quality of the video sequence. When the modulation cycle is no larger than 4, the distortion derived from key embedding can be neglected. Figure 6 illustrates the PSNR of the dinosaur sequence at the receiver side. It is worth noting that that the larger modulation cycle can degrade not only the PSNR, but also introduce PSNR fluctuation, while modulation cycle less than 4 can provide a good quality of video.

Figure 7 illustrates the number of error bits found in the detection of all the 200 bits in a frame against the modulation cycle C. The downscaling in the transcoder reduces half of the width and height of the original video. This procedure reduces the blocks in each field, but does not have too much impact on the detection quality. However, it can be seen that the requantization greatly impacts the detection quality when the modulation cycle is less than 3. As shown in Figure 7, when the quantizer in the requantization (denoted by "new quantizer" in the figure) is higher and the quantizer in the source encoding (denoted by "old quantizer" in this figure) is closer to half of "new quantizer," more error bits appear in the detection procedure. When the modulation cycle is more than 4, errors have almost disappeared.

Figure 5. The effect of security management on video

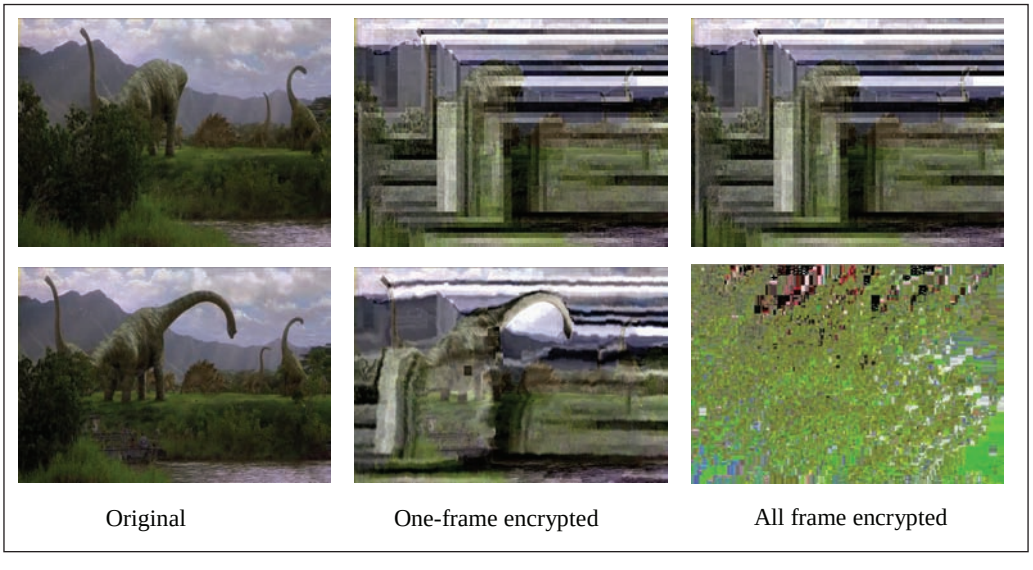


Figure 6. The PSNR of frames and the probability of successfully detecting 200 bits in a frame changed with the modulation cycle at the receiver

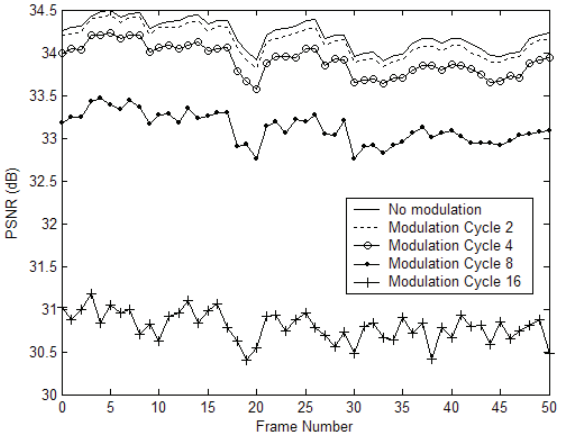


Figure 7. Average error bits in total 200bits embedded in an I-frame after transcoding with different modulation cycles and quantizers

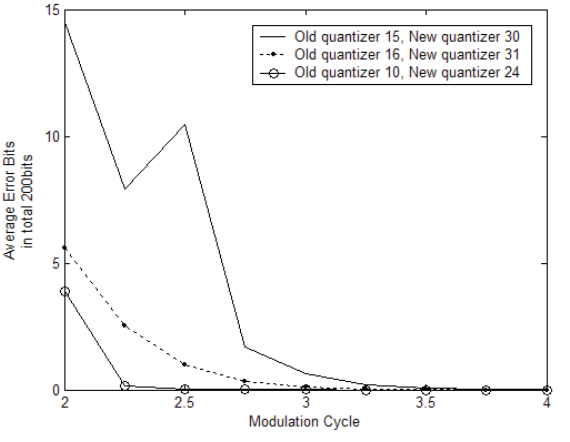
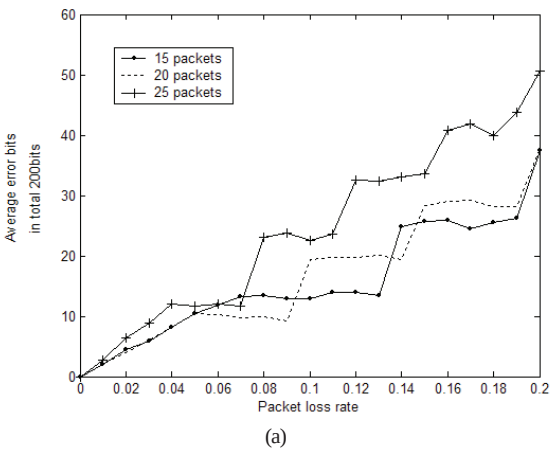
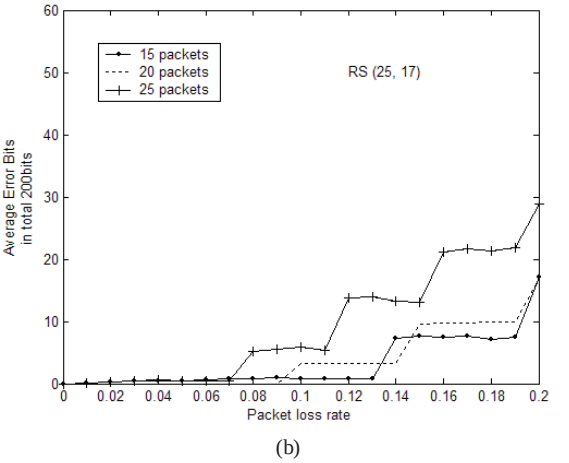


Figure 8. Average error bits in total 200bits of a GOP by using different packet loss rates, (a) RS code is not used, while (b) RS (25, 17) code is used



(a)



(b)

Figure 8 reveals the average error bits when receiving 200 bits data vs. the packet loss rate in the network. It can be seen that the extracted data error rate in a GOP rises as the packet loss rate increases. Usually the bitstream of an I-frame is divided into more than 10 packets for transmission in the network. As a result, key information is distributed into all the packets and the loss of packets leads to some error bits of the extracted key message.

As for the coding speed, Table 1 shows the coding time between the key embedded coding scheme and pure MPEG-2 encoder without data embedding. We can find that after the introduction of the key embedding algorithm, the processing time is only increased by around 6%.

Simulation of Routing Protocols

Preliminary simulations on AODV have been conducted in order to validate the choice of the routing protocol. The objective here is to have a qualitative evaluation of the routing protocol. Simulations have been conducted using NS2 simulator.

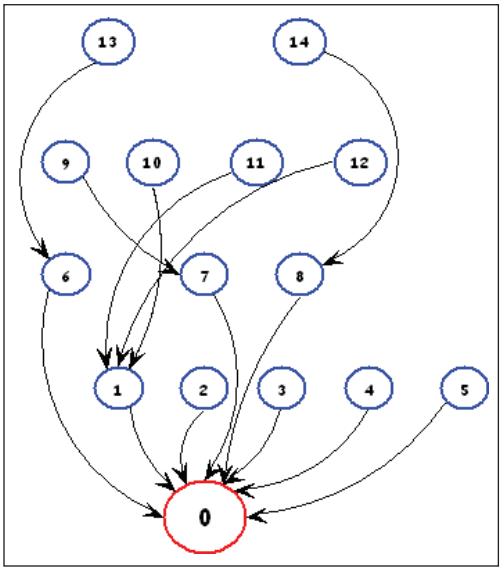
The arrows in Figure 9(a) represent the stream paths and we can see that the nodes are choosing the shortest paths to reach the monitoring center in order to reduce the number of hops per path in comparison with an architectural network.

Figure 9(b) reveals the volume of traffic received by each node in the scenario where a few cameras are placed at difference floors in a building and the distance between the nodes are greatly exaggerated (we do not consider the effect of reverberation against obstacles here). The figure shows that the monitoring center is the bottleneck of the architecture. This is inevitable in a monitoring system where all the streams are converging in one point. However, this phenomenon implies that the overall capacity is limited by the performance of the monitoring center.

Table 1. Complexity of the key embedding algorithm

Sequence	*Dinosaur*	*Live-captured*
Encoding speed without embedding (frame/sec)	35.45	37.27
Encoding speed with embedding (frame/sec)	33.50	35.00
Increased processing time (%)	5.8%	6.5%

Figure 9(a). Topology of a small monitoring system

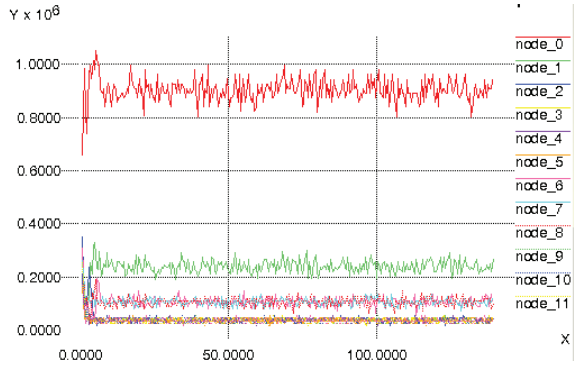


FUTURE TRENDS

With the continuing need for video surveillance in both fixed and remote locations, new advances in wireless networking would enable the development of a more secure, highly reliable wireless video network capable of supporting real-time high speed, high resolution video, and meanwhile maintaining the highest levels of data and network security without impacting the video stream. Technical trends and key issues in the wireless video system may include:

- **Load balanced routing protocols:** One problem of the routing protocol is that it is not reactive to the load in each node. Under the particular topology, if a node has a more critical location than others, a large portion of the traffic may converge toward the node and it may probably collapse under the heavy traffic. It would be more desirable for an ad hoc network that the routing protocol

Figure 9(b). Bandwidth of nodes in an ad hoc network under converging multimedia traffic



fairly distributes the traffic load among the nodes.

- **Local misbehavior detection system:** The system also needs to detect misbehaving neighbors. Only a few recent studies (e.g., Kargl, Klenk, Schlott, & Weber, 2005; Marti, Giuli, Lai, & Baker, 2000) have been conducted and reported in this field. Besides, in our case, misbehavior detection capability is limited by the computational power of the nodes. We hope to find an adaptive mechanism to suit our applications.
- **Scalability:** As demonstrated by the simulation results of our network layer, the monitoring center, as the only nondistributed component, is the bottleneck of the system. Some solutions must be found to scale the network size as far as possible.

CONCLUSION

A distributed video surveillance system typically consists of many video sources distributed over a wide area, transmitting live video streams to a central location for processing and monitoring. However, in the traditional wire-line solution, the deployment and maintenance of large-scale video surveillance system are often expensive and time-consuming. Thus there have been hot interests in wireless solution. But the practical implementation of wireless surveillance system still faces the challenges of framework design of wireless network, video processing, video data transmission, video quality control, and system security. Among them, the system security is the most challenging problem and also is the main concern in this chapter.

This chapter has presented the state-of-the-art cross domains of wireless communication, video processing, embedded systems, and security, through the design of a new secure video surveillance system. This system is based on the 802.11g ad hoc wireless infrastructure. Intel IXP425 network processors are used as the basic processing unit. A media-dependent video encryption scheme, including reliable data embedding technique and real-time video encryption algorithm, has been proposed and implemented to enable the system to work in an open and insecure wireless environment. The presented system offers several unique advantages: (1) it provides high security guarantee; (2) it does not require expensive access points/routers; (3) it can be readily deployed since it is built upon the existing wireless ad hoc infrastructure; and (4) it is robust in the presence of and adaptive mechanism and error-prone channel. This chapter would serve as a good reference for solving the issues of wireless multimedia and would bring new insights on the interaction of different technologies within the cross application domain.

ACKNOWLEDGMENT

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KEY TERMS

Ad Hoc Network: A local area network created for a specific purpose and established for a single session and does not require a router or a wireless base station. Specially, a wireless ad hoc network is a self-organized computer network with wireless communication links.

Discrete Cosine Transform (DCT): A Fourier-related transform algorithm that is widely used for data compression. DCT converts data (pixels, waveforms, etc.) into sets of frequencies and expresses a function or a signal in terms of a sum of sinusoids with different frequencies and amplitudes. It is often used in signal and image processing, especially for lossy data compression.

GOP: The group of pictures (GOP) is a group of successive pictures within a MPEG-coded film or video stream. A GOP consists of all the pictures in successive two GOP headers.

Network Processor: An integrated circuit that is optimized for networking and communications functions, typically programmable CPU chip.

Scalability: A property of a system, a network, or a process that can be modified to fit the problem area, that is, scaled to perform well with large-scale users.

Surveillance System: A closed-circuit television system used to monitor something.

Watermarking (Digital Watermark): A technique used to add hidden copyright notices or other verification messages in a digital signal or video so that it cannot be detected by a standard playback device or viewer.

Wireless Network: A telecommunications network whose interconnections between nodes use standard protocol, but without the use of network cabling.

Chapter XXXIII
Cutting the Gordian Knot:
Intrusion Detection Systems in Ad Hoc Networks

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ABSTRACT

Intrusion detection in ad hoc networks is a challenge because of the inherent characteristics of these networks, such as, the absence of centralized nodes, the lack of infrastructure, and so forth. Furthermore, in addition to application-based attacks, ad hoc networks are prone to attacks targeting routing protocols. Issues in intrusion detection in ad hoc networks are addressed by numerous research proposals in literature. In this chapter, we first enumerate the properties of ad hoc networks which hinder intrusion detection systems. After that, significant intrusion detection system (IDS) architectures and methodologies proposed in the literature are elucidated. Strengths and weaknesses of these works are studied and are explained. Finally, the future directions which will lead to the successful deployment of intrusion detection in ad hoc networks are discussed.

INTRODUCTION

Wireless ad hoc networks have attracted extensive attention among researchers in recent years. As the research activities matured, it has been widely realized that security in such networks is a major issue, and an extremely challenging one. The challenge arises mainly from the inherent

characteristics of ad hoc networks. Chief among the characteristics, which affect the design of an effective security framework for such networks, are the highly distributed, decentralized, and dynamic natures of ad hoc networks. These properties, coupled with the lack of infrastructure in ad hoc networks, introduce some unprecedented issues, which are absent and never been explored in conventional networks.

A typical security system consists of two major components. The first is the intrusion prevention mechanism that aims to control access to the system and relies mainly on cryptographic techniques. The second one is the intrusion detection system that tries to detect if the prevention mechanism has been compromised by intruders, and if so, come up with an appropriate response to combat such intrusions. The intrusion detection system (IDS) thus forms the second line of defense (Nadkarni & Mishra, 2003).

Cryptographic techniques rely on secure key management and key distribution which require supporting infrastructure. The lack of infrastructure makes it extremely difficult to implement cryptographic access control mechanisms in ad hoc networks. This makes intrusion detection all the more important for such networks. However, it turns out that the inherent characteristics of ad hoc networks render conventional IDS unsuitable for such networks. This has spawned the research in ad hoc IDS design (Brutch & Ko, 2003).

This chapter illustrates the difficulties in providing an efficient intrusion detection system for ad hoc networks. In doing so, it discusses in detail interesting ad hoc IDS models proposed in literature. The strengths and weaknesses of these models are explained and promising future directions for cutting the Gordian knot of ad hoc IDS are discussed.

BACKGROUND

Although various analyses on intrusion detection mechanisms can be seen in the literature, only few qualify as significant. Mishra, Nadkarni, and Patcha (2004) give a detailed overview of various ad hoc IDS architectures and methodologies. They offer an extensive analysis and understanding of IDS in ad hoc networks. A comprehensive comparison between various proposed intrusion detection systems for ad hoc networks are discussed. Selected architectures and detection strategies explained by Mishra et al., which were found significant, are detailed in this writing.

Zhang, Huang, and Lee (2005) propose an evaluation environment for MANET (mobile ad hoc network) intrusion detection systems. They emulated routing attacks and evaluated application-based intrusion detection architectures over it. The work introduces a novel concept of evaluating ad hoc IDS models using known attacks. Routing attack libraries are used, which exhibit attack scenarios over the IDS model under-evaluation. The IDS models are evaluated for operational cost and effectiveness. Detection accuracy and false alarms are the primary evaluation parameters for assessing of the IDS model, in terms of detection effectiveness. The work is significant in providing a test-bed for ad hoc IDS models. Similarly, Little (2005) proposes a test-bed called TeaLab for ad hoc IDS design.

Concurrent to simulation-based ad hoc test-beds, Yang and Baras (2003) mathematically analyze vulnerabilities in ad hoc networks. The authors provide a great deal of understanding to the attack possibilities in ad hoc domain. Mathematical methods find attacks exhaustively. In this theoretical analysis all possible attacks are hypothesized. This comprehensive vulnerability analysis aids the design of an effective ad hoc IDS design.

CHARACTERISTICS OF AD HOC NETWORKS

Ad hoc networks differ from native wired/wireless networks in various aspects. These unique characteristics of ad hoc networks render typical security systems unsuitable (Awerbuch, Curtmola, Holmer, Rubens, & Nita-Rotaru, 2005; Papadimitratos & Haas, 2002). The fundamental concept of ad hoc networks is to have seamless connectivity without infrastructure or centralized control. The lack of

infrastructure and a centralized control node makes it hard for security systems to be implemented. Furthermore, factors such as mobility, physical protection, and so forth affect the design of effective security models for ad hoc systems. These factors are enumerated below.

Lack of Infrastructure

Ad hoc networks do not have a fixed infrastructure. Typically, in conventional networks, the infrastructure provides a secure location for the implementation of critical security mechanisms (Debar, Dacier, & Wespi, 1999). Due to the absence of infrastructure, ad hoc networks do not provide a safe and efficient location to implement the security system. Additionally, operations such as control, maintenance, and other administrative functions have become hard in a distributed and infrastructure-less network. The only and apparent resort is to install these critical modules in end-user nodes. Implementing critical security systems in unreliable end-user nodes pose a real challenge.

Absence of a Central Authority

Conventional network have traffic concentration areas, otherwise called choke points, where security systems can be placed and implemented efficiently. Control nodes are placed in these choke points to monitor and control the network. Absence of centralized authority makes the network monitoring and control a challenging issue for ad hoc networks.

Every node in an ad hoc network has equal responsibility in network functions, such as routing, maintenance, and so forth. This unique characteristic will distribute the control authority to all nodes in the network. Nodes have to rely on other neighbor nodes for routing and data forwarding. In other words, nodes have to trust neighbor end-user nodes for critical functions. As neighbors can be potential attackers, trusting unknown neighbors is precarious to the integrity of security and other critical systems.

The above two issues are the crux of the security concern in the ad hoc network paradigm. The following are additional factors which also affect ad hoc network security design, but to a lesser degree.

Wireless Links

In respect to security, wireless links are the weakest. This is due the omnipresence of wireless channel and ease of physical access to the channel. Attacks such as eaves-dropping, active masquerading, and so forth are more possible in wireless networks than in a wired network. Furthermore, the most notorious of all attacks, the denial-of-service (DoS) attacks, can be achieved easily in wireless networks by jamming the wireless channel or by routing attacks.

Poor Physical Protection

Usually, the nodes in an ad hoc network are mobile and easily accessible physically. This raises concerns of physical protection of these devices. A single compromised node can bring down the entire network due to its prerogatives in the network.

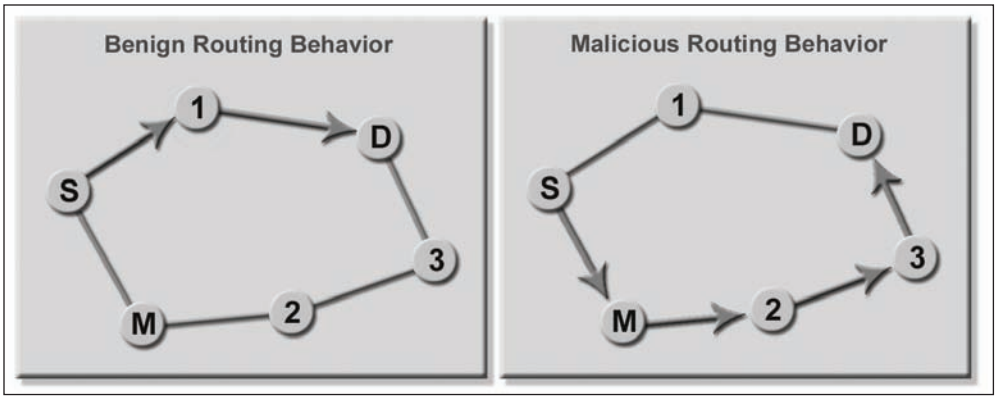
Energy Constraints

Since ad hoc network nodes are mostly mobile and wireless, energy constraints are also a security issue. Typical symmetric encryption algorithms such as 3DES (triple data encryption standard), ADES (advanced encryption standard), and asymmetric encryption algorithms such as RSA (Rivest, Shamir, and Adleman) and its variants incurs high computation which may drain the battery of the mobile node. Additionally, rnergy-targeted attacks such as SDT (sleep deprivation torture), which aims to drain the mobile node's battery, also need consideration while designing ad hoc security system (Jacoby, Marchany, & Davis, 2004).

Unsuitability of Static Configurations

The obvious and immediate security solution for infrastructure-less and decentralized network is to provide static security systems installed in nodes. Ad hoc networks are mostly implemented over

Figure 1. Ad hoc routing insecurity: Route invasion



mobile nodes. Mobility introduces transient associations due to the dynamic nature of the network. Therefore, prediction of security configuration in a dynamic ad hoc network may not be possible. Also, static security systems have poor adaptability to new attacks, which renders them inefficient.

Delay Constraints

Security systems are delay-sensitive. Especially in highly dynamic environments, delay guarantees are necessary for the security system to function properly. This necessity arises from the transient associations in the ad hoc network, which is discussed in the succeeding section. However, delay guarantees are hard in dynamic networks because of wireless connectivity and mobility.

Transient Associations

The high mobility of nodes in ad hoc environment makes connections between the nodes transient. Therefore, a node will not be able to get security specific information from its neighbor node permanently. In other words, the time frame for particular information to be valid in the ad hoc network becomes very small because of transient associations.

Routing Security

Routing security is an issue that is unique to ad hoc networks (Papadimitratos & Haas, 2002). Conventional networks have security systems implemented in IP, transport, or application layer. Only ad hoc networks need security at the routing layer or protocol. The need arises from the nature of ad hoc network technology where every node can function as a router. Apparently, this has raised new challenges and issues, since securing a routing protocol has never been an issue for security system designers for legacy networks.

Any node in an ad hoc network can add/modify/delete routes. This functionality is the root cause of the vulnerability of ad hoc routing protocols. A malicious node can send malicious routing control messages to its neighbors. Since ad hoc networks are highly distributed, decentralized, and dynamic systems, preventing or detecting a malicious routing message becomes difficult. Moreover, semantically distinguishing between malicious and benign routing messages is infeasible. Routing insecurity introduces new attack possibilities. Active attacks such as route invasion, and route disruption, cause active damage to the network routing functions (Awerbuch et al., 2005). Route invasion and disruption attacks aim to modify, add, or delete benign routes by sending malicious routing information

over the network. Passive attacks such as route monitoring and so forth try to eavesdrop for stealing sensitive information (Kong, Hong, & Gerla, 2003). To illustrate some of the difficulties and to familiarize routing insecurity in ad hoc networks, a trivial attack scenario is considered.

Let us examine route invasion, which is a trivial but destructive attack. In Figure 1(a), the benign route between S and D is through 1. In Figure 1(b), Node M sends a malicious routing control message, stating that it has a better route to D than through Node 1. This modifies the path for S → D from S → 1 → D to S → M → 2 → 3 → D. The modified path is not only inefficient; it includes the malicious Node M into the path. This extends the attack possibilities for the malicious node M on node A or B. To thwart intrusion detection, Node M can impersonate Node 1 and can provide falsified routing information which supports its cause.

Due to the absence of centralized authority and infrastructure, Node S has no trusted arbiter to get advice regarding whether the announced path is benign or otherwise. Malicious Node M has free access to the wireless channel and can exhibit anonymous routing attacks over S.

Static crypto systems fail here, due to poor physical protection, energy, and delay constraints. In the absence of centralized authority, dynamic crypto systems are not possible. Critical security systems such as key management, admission/access control, and authentication become hard to implement due to the lack of infrastructure. Analogous to IP spoofing, ad hoc routing protocols are prone to spoofing. However, unlike IP, spoofing in ad hoc networks is done at the routing protocol rather than the IP. Generically, ad hoc security needs to prevent or detect spoofing. However, the issue is more serious than in IP, since the target of the attack is the routing protocol itself.

Mobility and transient associations and dynamicity make the detection of malicious routing control messages impractical. In the above example, Node S will not be able to determine with its local knowledge whether Node M is on a shortest route to D or acting maliciously. Because, even if Node M is not on a shortest/optimal path to Node D now, due to changing topology, that may change at a point of time in the future. In other words, a malicious behavior highly resembles another benign behavior. Therefore, intrusion detection becomes very challenging.

INTRUSTION DETECTION TECHNIQUES

Intrusion detection systems are mechanisms which provide a "second wall of defense" (Nadkarni & Mishra, 2003) for the network system. In other words, IDS is a backup, in case the frontline security mechanisms fail. Therefore, IDS fundamentally assumes that cryptographic systems do not prevail or have failed. As mentioned earlier, IDS in ad hoc networks cannot trust information from other nodes. This limits the knowledge sharing between the nodes. Knowledge in IDS is the new benign/malicious behavior patterns. Typical systems use an arbiter (centralized) node to facilitate knowledge sharing. However, the absence of any centralized node in ad hoc networks renders knowledge sharing unreliable. Unreliable information in a security system is worth no information at all.

Conventional IDS are functional in application layer and monitor and detect malicious behavior exhibited by applications, such as, telnet, FTP, SMTP, and so forth. In rare cases, relatively simple IDS, such as firewalls are implemented in the IP layer. However, ad hoc networks' necessity for routing security has brought forth the need to implement IDS, which monitors and detects routing protocols, such as AODV, OLSR, DSR, and so forth. An IDS design for a routing protocol is an unexplored area of research. The requirements of IDS for a routing protocol differ vastly from the conventional IDS mechanisms.

Research in ad hoc IDS design is still in the rudimentary stages. Some research works (Hijazi & Nasser, 2005) on ad- hoc IDS, which try to cut the Gordian knot, follow strongly the IDS design methodologies of native IDS counterparts. In addition, most of the IDS models proposed in the literature focus on application-level IDS. The assumption that application level IDS for ad hoc network will suffice are the major weakness of

these works. Therefore, though these IDS models consider ad hoc network characteristics and provide a decentralized and distributed IDS, they fail to address the routing insecurity.

Zhang, Lee, and Huang (2003) propose a distributed and decentralized IDS system at the routing layer but fail to describe the routing-level IDS model. Their work is similar to other research models on ad hoc IDS design, which provid application-level IDS. Eventually, Huang and Lee (2004) analyze AODV intensively and provid a strong understanding of AODV and a guide to design an AODV IDS at routing layer. However, they fail to state the statistical methodologies used in the IDS design.

In what follows, the existing IDS models are enumerated and its strengths and weaknesses are analyzed. Additionally, the feasibility of implementation of these methods is studied.

A SIMPLE IDS

Before venturing into the realm of ad hoc IDS designs, a short primer on a simple IDS model will be helpful. The fundamental working of an IDS is shown in Figure 2. A typical IDS model consists of three modules: detection module, response module, and audit trails (Athanasiades, Abler, Levine, Owen, & Riley, 2003). Audit trails is a database which stores known normal behavior or anomalous behavior patterns. The detection modules analyze the observed behavior by comparing them with the known behavior patterns in the audit trails' database. There are two types of pattern matching methodologies: misbehavior detection and anomaly detection. Misbehavior detection uses known malicious behavior patterns for comparison at the detection module. Anomaly detection uses known normal behavior patterns and measures the deviation of the node's behavior from the known normal behavior patterns.

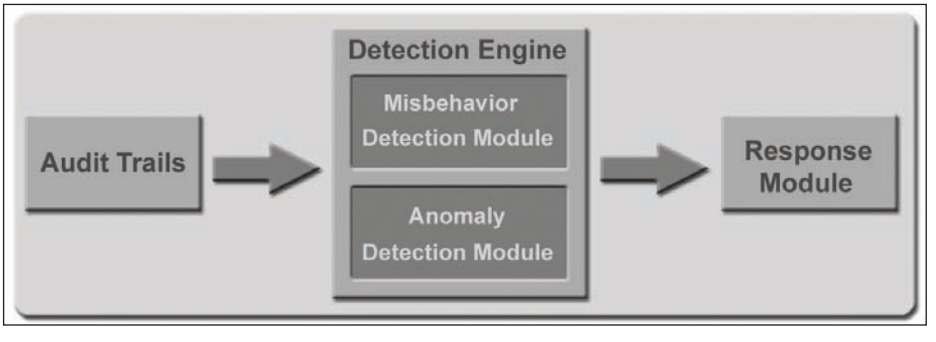
The main strength of misbehavior detection is that the probability of false alarm is quite low. However, the probability of deduction is also low, as unknown attacks will skip detection. On the contrary, anomaly detection increases the probability of detection at the cost of increased false alarm rates. Typically, both mechanisms are used in concurrence to define a tradeoff point between probability of detection and false alarm rates.

AD HOC NETWORK IDS REQUIREMENTS

Having seen the fundamental operation of an IDS, this section explores the essentialities and challenges behind an efficient ad hoc IDS. Understanding the difference between an ad hoc IDS and the conventional IDS will help us to appreciate the requirements of an ad hoc IDS. Also, this will aid us to understand the strength and weakness of each proposed IDS models.

The notorious Mitnick IP (Shimomura & Markoff, 1996) spoofing attacks are classic examples which demonstrate the destructive capabilities of routing attacks. Legendary Mitnick used IP address spoofing to attack government and commercial networks by feigning IP address. In ad hoc networks,

Figure 2. A simple intrusion detection architecture



spoofing network address becomes naïve, since an attacker can get hands on the routing protocol itself. The gamut of attack possibilities is infinite (Awerbuch, Curtmola., Holmer., Nita-Rotaru., & Rubens., 2004). In the following sections, we will explore the factors that affect ad hoc IDS.

Knowledge Limitations in Audits

To assess whether a behavior is malicious or benign, a node needs knowledge about different behaviors. It is evident that with more knowledge, efficiency of distinguishing between malicious and benign behaviors increases. In conventional networks, knowledge is shared using a trusted arbitrary node. Absence of a centralized node in ad hoc networks limits the knowledge sharing. Knowledge sharing is precarious in a decentralized and distributed network. A malicious node can cast malicious information which may affect the integrity and security of IDS itself. When a node receives contradictory information from benign and malicious nodes, a decision dilemma occurs. IDS will not be able to decide which information is correct. To avoid this high risk scenario, the nodes can only resort to local knowledge. Local knowledge is information gained through the node's its own experience.

It can be argued that if the number of benign nodes is more than the malicious nodes, knowledge sharing will be reliable. It is true to some extent. According to Byzantine agreement (Lamport, Shostak, & Pease, 1982), for the distributed global knowledge to be reliable, benign nodes should be greater than two-thirds of the total number of nodes. However, ad hoc networks have an interesting attack scenario, which can thwart Byzantine agreement even in the presence of sufficient benign nodes. An attacker using address spoofing can create nonexistent neighbor nodes and can emulate malicious behavior for the nonexistent nodes. This gives the attacker the advantage of controlling the apparent number of malicious nodes in the network, thereby, invalidating Byzantine agreement.

It is important to consider that audit trails from routing protocols differ significantly from audit information from application layer protocols. Audits from application layer protocols record user behavior (Balajinath & Raghavan, 2001), such as login attempts and failures, access rate, and so forth. Whereas, audits from routing protocol record node behavior such as mobility, speed, connectivity, and so forth. The user behavior feature differs distinctly from routing protocol behavior features. Hence, the methodologies analyzing the audit trails have to be revised.

Detection Strategies

Detection methodologies can be classified as rule-based, statistical, and hybrid, which are explained below.

Rule-based detection use static rules to determine maliciousness in behavior. Rules are a set of logical conditions, and when these conditions are met, the behavior is categorized as malicious. Let us consider a simple rule to illustrate. Failure of three or more consecutive login attempts can reasonably be used to decide that the behavior is malicious. More complex rules are formed using typical logical reasoning mechanisms such as expert systems. Static rule-based approaches which are practical in conventional IDS fail due to the dynamic nature of ad hoc networks. The dynamic behavior creates transient connections which makes intrusion detection through static rules almost impossible. Furthermore, static security systems are known to perform inefficiently in dynamic and distributed systems.

Statistical approaches uses probability estimation theory (Duda, Hart, & Stork, 2000) to allow some flexibility to crisp logic and rule-based detection strategies. In statistical approach, probability of behavior being malicious is determined by statistically analyzing the known behavior patterns. However, statistical analysis of routing behavior in ad hoc networks is inconclusive and so is statistical IDS in ad hoc networks. Conventional IDS systems use statistical approach (Verwoerd & Hunt, 2002) after very intensive data analysis (Bykova, Ostermann, & Tjaden, 2001) and are derived using computational intelligence methodologies (Duda, Hart, & Stork, 2000). These analyses are done for audit trails from application layer protocols. The

lack of similar research on routing behavior audits for ad hoc networks raises an interesting question on the suitability of statistical approaches for ad hoc IDS. This is another unexplored research area in ad hoc security.

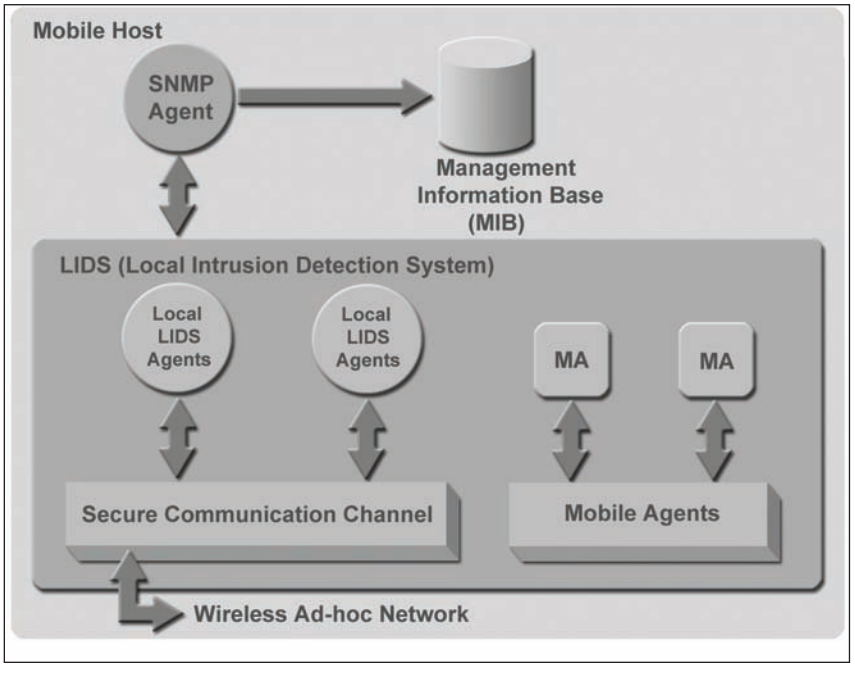
H*ybrid detection strategies* combine the above two approaches. Hybrid mechanisms are expected to perform better than the two approaches, since they incorporate semantics (rule-based systems) and statistical intelligence. This is in fact supported by conventional IDS models where hybrid systems are usually superior.

In the ad hoc IDS paradigm, these detection methodologies face numerous shortcomings. A major impediment is the lack of features describing a routing behavior. Features are parameters or values describing a behavior. For example, the number of server logins is a feature describing a user behavior over server-client-based application layer protocol. Similarly, delay between two routing requests is an example of a feature describing a routing behavior. Typically, in a user behavior, the number of features can extend from 40-100 or more. On the contrary, a routing control message has very few independent features. The content of a routing message is kept as minimal as possible to increase the routing efficiency. This has decreased the features set describing a routing behavior. Different protocols have different features and the feature set is highly protocol dependent.

Inference

It can be inferred that an ad hoc IDS model requires a complete reconstruction of the current conventional IDS architecture. An IDS which functions with only local knowledge, without a centralized node, adapts to dynamic environments, and efficiently identifies malicious behavior will be a *magnum opus* in the field of ad hoc network security. Additionally, functions such as learning new attacks (part of adaptation) without corrupting the local knowledge base will be beneficial (Hossain, Bridges, & Vaughn, 2003; Pokrajac & Lazarevic, 2004). Learning is itself a dynamic process; therefore learning in a highly dynamic, distributed, decentralized, and insecure environment will be challenging.

Figure 3. LIDS architecture



IDS MODELS

Intrusion detection systems have two major components: architectures and methodologies. IDS architectures are the design which depict the overall functioning of the IDS, like the system shown in Figure 2. On the other hand, IDS methodologies are models for detection strategies and their supplementary functions, which are the internal functions of the IDS. Efficiency of the IDS depends both on the architecture and methodologies. Mishra et al. (2004) analyzed various IDS architectures systematically. Succeeding sections discuss about these IDS architectures following Mishra et al.'s (2004) analysis.

Most of the architectures proposed in the literature assume that the methodologies used in conventional IDS model will suffice in an ad hoc environment. In the succeeding sections, the strength of this assumption is analyzed. Furthermore, it has been observed that research work which focuses on IDS architectures does not consider the limitations of IDS methodologies and vice versa.

Architectures

IDS Using Mobile Agents

IDS system is of two types: host-based and network-based. Host-based IDS, as the name implies, runs on individual nodes and functions partially or completely autonomously. On the other hand, in network-based IDS, a centralized node is used to monitor and detect intrusions on the network. It is obvious that network-based IDS is not possible in ad hoc environment because of the absence of a centralized authority.

Mobile agent is a software module, which aids in distributed host-based intrusion detection. The software module traverses through the nodes in the network to accomplish a particular task, such as collecting information, processing information, and so forth. Mobile agents try to emulate network-based intrusion detection by using a collective host-based IDS. The mobile agent provides a good framework to create distributed host-based intrusion detection system. However, mobile agents themselves pose a security threat to the ad hoc network. This is detailed in the following sections by analyzing the IDS architectures that uses mobile agents.

Local Intrusion Detection System Using Mobile Agents

LIDS (Patrick, Olivier, Jean-Marc, Bernard, Ludovic, & Ricardo, 2002) is an application-based IDS architecture for providing intrusion detection in ad hoc network. The IDS architecture is shown in Figure 3, which consists of agents. Agents are host-based intrusion detection modules running on all nodes. The architecture utilizes SNMP (simple network management protocol) to communicate with the neighbors.

A local LIDS agent is responsible for detecting the attacks locally. LIDS agents help neighbor nodes to decide on a suspected intrusion. Also, it receives updates of new attack patterns from the neighbor nodes. The attack patterns are stored in the information base. The MIB (management information base) agent is used to manage the information base. Between the neighbor nodes, SNMP is used to exchange information such as new attack patterns, decisions/responses, and so forth. The MIB agent is responsible for retrieving and sending information to/from neighbors using SNMP. The authors exploit the cooperative nature of ad hoc network by sharing the information about new attack patterns between the nodes.

Additionally, mobile agents are software modules which function autonomously for a dedicated task. For example, the LIDS may designate a mobile agent (MA) to determine the probability of a particular behavioral pattern to be malicious. The MA will autonomously travel between nodes and gather evidence from traversing nodes' MIB.

This approach is relatively naïve. First, the authors assume SNMP is secure in an ad hoc environment. In a network, where routing is insecure, SNMP is not as secure as in a conventional network. Second, as mentioned in the earlier section, knowledge sharing is highly insecure in an ad hoc network. This leads to the insecurity of the LIDS system itself. Compromised nodes can announce misleading intrusion detection informa-

tion, which will eventually corrupt the information base of the entire network. Finally, in a network with transient associations, feasibility of mobile agents is questionable.

Stationary Secure Database IDS

Andrew (2001) proposes an IDS architecture which consists of a stationary secure database (SSD). Nodes post new information and decisions into this database. The architecture is simple, as shown in Figure 4. Only detection processing is done on the host and the information is stored in a secure stationary centralized point.

The other components of the IDS are typical, namely, misbehavior detection module (MDM), anomaly detection module (ADM), and communication port. These components form the mobile agent. A local intrusion database is also used to store node specific attack patterns and temporary information. The mobile agents will publish the newly found attack pattern to the SSD, only after a certain level of confidence is reached. The communication port is used to communicate with the other nodes' host-based intrusion detection system.

Apparently, it can be seen that stationary secure database (SSD) conflicts with the ad hoc characteristic of the absence of centralized authority. Even if a node is voted as the centralized node using trust mechanisms, there is no surety that the node will behave benignly. Furthermore, a malicious node can corrupt the SSD by sending incorrect intrusion detection information. SSD creates a hot spot, which is a single point of failure. Additionally, SSD assumes cryptographic mechanisms on the communication between the IDS and SSD. This violates the fundamental principle of IDS, which assumes "*no existence of cryptographic mechanisms.*"

Modular Intrusion Detection Architecture

Kachirski and Guha (2002) propose an IDS where the intrusion-detection system is modularized into various submodules, as shown in Figure 5. The submodules are network monitoring, host monitoring, decision making, and response (action) modules. The modules are implemented in mobile agent framework. Network monitoring is packet monitoring over the network. Host monitor-

Figure 4. Secure stationary database architecture

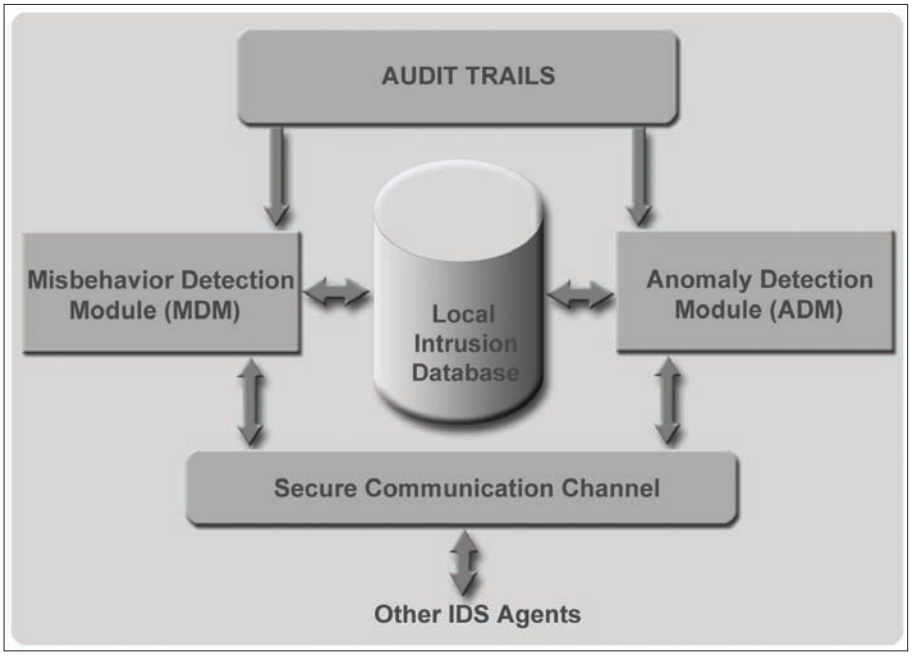
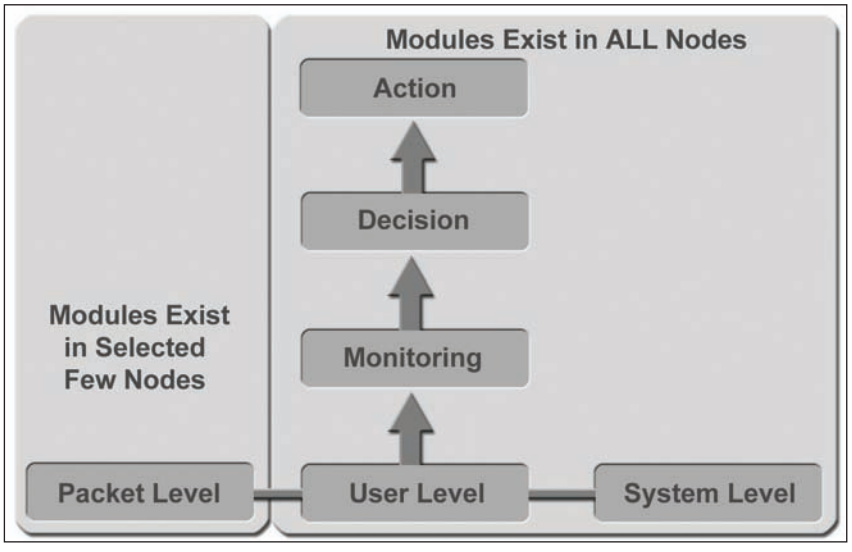


Figure 5. Modularized IDS architecture



ing is monitoring of user behavior. A host-based monitor module exists in every node; however, network-based monitor exists only in a selected few. Decision making and response modules exist in every node.

The entire ad hoc network is segregated into clusters. Each cluster has a cluster-head, which runs the network-based monitoring. Therefore, packet-level monitoring is done by the cluster-head. Individual nodes use the packet-level audits from the cluster-head to improve the performance of the host-based intrusion detection system.

The strength of this IDS architecture is augmentation of network-based IDS with host-based IDS. The combination of these mechanisms has proved very efficient in conventional IDS. Furthermore, the authors have eliminated the single point of failure by distributing the cluster heads. This also distributes the management load between cluster-heads of the network. Also, host-level basis of decision making on an intrusion makes this approach robust against attacks on the IDS itself.

However, the architecture's trust on the cluster-head is its weak point. Malicious behavior of a cluster-head will lead to the compromise of all nodes under its control. In additions, similar to the other two mobile agent-based IDS, this architecture assumes secure routing, which may not be true.

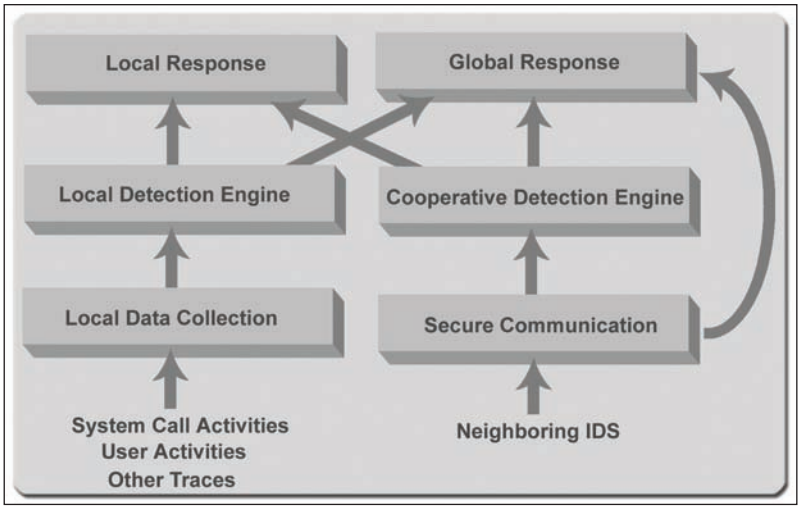
Distributed IDS

Distributed IDS differs significantly from mobile agent-based IDS. Zhang, Lee, and Huang (2003) in their pioneering work propose a distributed IDS. The IDS architecture as shown in Figure 6 consists of local and cooperative intrusion detection engines. These detection engines are interfaced with their respective response modules.

A local intrusion detection system is a typical host-based IDS. The cooperative intrusion detection engine is used to decide globally about a particular behavior pattern. Collection of all cooperative detection engines on all nodes form a global intrusion detection engine. Semantically, Cooperative detection is analogous to network-based intrusion detection. However, global decision on behavior patterns will not dominate local decision. Nonetheless, global decision will aid local response. Few incorrect decisions about a behavioral pattern will not affect the global decision as more numbers of correct decisions will invalidate the incorrect decisions.

Local detection engine functions autonomously, independent of other nodes' detection engines. The cooperative engine will not aid the local-detection engine for identifying a malicious behavior pattern. This prevents propagation of malicious or

Figure 6. Distributed IDS architecture



wrong detection to other nodes. However, the local response to an attack is aided by the cooperative detection engine. Furthermore, a global response is deduced by collecting information from various local intrusion detection engines of all nodes in the network. Eventually, this global response will be used for response action for that particular behavior pattern.

Although global decision sharing is secure comparing behavior-pattern sharing, the authors did not discuss how local intrusion detection relies on the global responses. Routing insecurity provides the ability to an attacker to create nonexistent nodes. Therefore, the attacker can emulate malicious behavior for these nonexistent nodes. Thus, the real majority of benign nodes will not help to guarantee security of the distributed IDS

Methodologies

TIARA

Techniques for intrusion-resistant ad hoc routing algorithms (TIARA) essentially an intrusion prevention model (Ramanujan, Ahamad, Bonney, Hagelstrom, & Thurber, 2000). TIARA is a conglomeration of innovative techniques which provides:

- Light-weight firewalls
- Traffic policing
- Intrusion tolerant routing
- Intrusion detection
- Flow monitoring
- Reconfiguration mechanisms
- Multipath routing
- Source initiated route switching

It aims to minimize the damage incurred on the ad hoc network by destructive attacks such as DoS, distributed denial of service (DDoS), and so forth. Routing and data traffic are protected by TIARA. TIARA is a distributed framework. TIARA is a highly efficient cross-layer intrusion prevention and detection mechanism. Exploring each of these techniques is beyond the scope of this chapter. Mishra has briefly discussed these techniques in his survey of ad hoc IDS.

However, it should be noted that intrusion detection is a module in the collection of techniques. The operational efficiency of the intrusion detection is unknown. Furthermore, tolerance to attacks is not the fundamental goal of an intrusion detection system. Unless the attackers are eliminated from the network or the attack is identified and segregated from benign traffic, the network is always under threat. Persistent attacks have high probability of success. Therefore, immediate response to attack

is critical. TIARA has no response system for intrusions.

Threshold-Based Detection

A simplistic approach to ad hoc IDS is threshold-based detection. Bhargava and Agrawal (2001) propose an ad hoc IDS which prevents internal attacks (attacks within the network). Internal attacks are exhibited by nodes belonging to the network which behave maliciously, either by themselves or when compromised. Each node maintains a local variable called "MalCount" for every other node, which is increased for a particular node if its behavior is suspicious. Thus the MalCount array in a node tracks the level or state of suspicion that the host node has regarding the other nodes. Each node shares its local state of suspicion with respect to a particular node with other nodes in the network using a special packet REMAL. When a node receives REMAL, it increases its local MalCount for the particular node under suspicion.

The authors overlooked many aspects of ad hoc security. First, malicious knowledge sharing using REMAL will have cumulative malign effect on the network. Second, the security of the REMAL packet is unknown. Eventually, the entire network can be under threat by trusting unreliable REMAL packets. The crucial aspect of the security of the IDS is not considered in this methodology. Furthermore, routing security is not addressed.

Another interesting approach called watchdog-pathrater, which also uses threshold, is proposed by Sergio, Giuli, Kevin, and Mary (2000). Watchdog-pathrater, as the name implies, has a monitor and evaluator. Unlike Bhargava and Agrawal's (2001) approach, Watchdog-pathrater functions independently and does not share information with other nodes. When a packet is forwarded to a neighbor node, the forwarding node listens and monitors how the node behaves upon receiving a packet. A benign node will forward faithfully, which is overheard by the monitor. However, when the node does not forward the packet, the pathrater increases the failure rate for the path. The monitor does not distinguish between maliciousness and node faultiness. Upon the failure rate reaching the threshold, the node is discarded from any path.

This method is analogous to fault-tolerance in typical routing algorithms. This method effectively detects and responds to malicious packet dropping attacks (sinks). However, it fails to address attacks such as route invasion, route disruption, and so forth.

State-Based Anomaly Detection

One of the interesting approaches in conventional IDS models are state-based intrusion detection. Michael and Ghosh (2000) incorporate a state-based model in ad hoc intrusion detection. They propose two anomaly detection methodologies, which use finite-state machines (FSM). FSM have proved successful in conventional IDS because of their adaptability and dynamic learning capability of new attacks.

Anomaly detection methods proposed by Michael and Ghosh (2000) used protocol states. In the first method, the sequence and frequency of protocol states are monitored. Intrusion is affirmed when a particular sequence deviates significantly from normal behavior patterns or the frequency of states exceeds a threshold. To increase robustness, their second approach uses probabilistic state-based intrusion detection. Each occurrence of a suspicious protocol state increases the probability of the behavior being malicious.

These two approaches are well suited for transport and application layer protocols, which have many protocol states, and the protocol states are predictable. For example, attacks such as, TCP SYN flood attack can be detected using this approach.

However, this is not true in the case of routing protocols. State sequence or frequency of states does not distinguish a malicious behavior from a benign one. Traditionally, FSM were used to extract semantics from user behavior through application-layer protocols. In the case of ad hoc routing protocols, semantics is not represented by protocol states, but factors such as current topology, mobility, connectivity, and so forth are.

FUTURE TRENDS

Research in ad hoc network security is in its embryonic stages. Ad hoc network IDS is even more rudimentary, since the quest for an efficient intrusion prevention mechanism is not over yet (Hubaux, Buttyan, & Capkun, 2001). Intrusion prevention and detection mechanisms are mutually productive for ad hoc security. Clearly, a concrete and practical IDS model for ad hoc networks is yet to be evolved.

Historically, conventional IDS systems were subjected to intensive research and analysis before becoming practical. Analogous to conventional IDS, ad hoc intrusion detection needs more research. It is eminent that consideration of ad hoc network characteristics plays a vital role in the denouement of the IDS model. In literature, most of the research focus was on IDS architectures. However, IDS in ad hoc networks require innovative detection strategies to resolve the issue pertaining to IDS in ad hoc networks.

To summarize, we enumerate below the observations made from the study of ad hoc IDS models proposed in the literature.

First, routing security should be the crux of the IDS. Similar to conventional IDS, intensive statistical analysis and research is required on the feasibility of statistical and rule-based detection methodologies, in respect to routing behavioral data. Routing control messages produce a new kind of audit trails. New features linked to the properties of routing control message have to be derived. These derived parameters will aid in analyzing the feasibility of various detection methodologies.

Second, the absence of a centralized node necessitates innovative adaptation in the IDS. Adaptation is the process of learning new attacks, attack resolving techniques (responses), as well as changing statistical parameters with respect to the ad hoc network environment. Adaptation in a highly dynamic network is an interesting and new challenge. Efficiency of various computational intelligence methods, which are also used in conventional IDS, has to be analyzed. Learning new attacks through intelligence in ad hoc IDS paradigm is an unexplored research domain.

Finally, the most significant ad hoc network characteristics which affect the IDS model are the three Ds: distributed, decentralized and dynamic nature. An IDS architecture which considers these three factors will essentially be efficient. However, the IDS architecture should also consider the limitations of detection methodologies.

CONCLUSION

The implementation of intrusion detection systems in ad hoc networks is hindered by the inherent characteristics of these networks. These characteristics were examined and their significance was observed. The differences between conventional and ad hoc intrusion detection systems are detailed. Requirements of an effective ad hoc IDS are studied. Various proposed IDS architectures and methodologies are explored and their strengths and weakness are discussed. The future of ad hoc IDS depends mostly on the statistical properties of ad hoc network's routing behaviors. Therefore, considerable research and development is required in this domain.

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KEY TERMS

Ad Hoc Networks: Ad hoc networks are loosely organized and configured network. There are no centralized nodes, such as routers, gateways, and so forth. All network functions are done by every node and thereby every node supports the network's functioning.

Anomaly Detection: Anomaly detection is a type of intrusion detection in which historical normal behavior of the network is used. Any deviation of a behavior from the normal will raise an alarm.

Audit Trails: Audit trails describe a network or node behavior. It contains values for a set of parameters, which is recorded in periodic intervals of time. The parameter set is called as the feature set and usually differs between different network environments, protocols, and systems.

Intrusion/Attack: Intrusion is a behavior of an external or internal node(s) with malign intent, which aims to affect other benign nodes in the network.

Intrusion Detection: Intrusion detection is the process of identifying and distinguishing malicious behavior from the normal network traffic.

Misbehavior Detection: Misbehavior detection is a complement to anomaly detection. In this type of intrusion detection, known intrusion behavior patterns are used. Any resemblance of a behavior with these patterns will result in an alarm.

Mobile Agents: Mobile agents are specialized software which move between nodes to accomplish their assigned tasks, such as data collection and so forth.

Chapter XXXIV
Security in Wireless Sensor Networks

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ABSTRACT

In this chapter we present the growing challenges related to security in wireless sensor networks. We show possible attack scenarios and evidence the easiness of perpetrating several types of attacks due to the extreme resource limitations that wireless sensor networks are subjected to. Nevertheless, we show that security is a feasible goal in this resource-limited environment; to prove that security is possible we survey several proposed sensor network security protocols targeted to different layers in the protocol stack. The work surveyed in this chapter enable several protection mechanisms vs. well documented network attacks. Finally, we summarize the work that has been done in the area and present a series of ongoing challenges for future work.

INTRODUCTION

Recently, wireless sensor networks (WSN) have gained great popularity, mainly because they provide a low cost alternative to solving a great variety of real-world problems (Akyildiz, Su, & Sankarasubramaniam, 2003). Their low cost enableds the deployment of large amounts of sensor nodes (in the order of thousands, and in the future perhaps millions), which most of the time operate under harsh environments. WSN present extreme resource limitations, mainly in available memory space and energy source. Both limitations represent great obstacles for the integration of traditional security techniques. The highly unreliable communication channels that are used in WSN and the fact that they operate unattended make the integration of security techniques even harder.

Wireless sensor networks today offer the processing capabilities of computers of a few decades ago and the industry's trend is to reduce the cost of wireless sensing nodes while maintaining the

same processing power. Based on this idea, many researchers have started to face the challenge of maximizing processing capabilities and reducing energy consumption while protecting sensor networks from possible attacks.

BACKGROUND

WSN have many more limitations than other traditional computer networks. Due to these limitations, it is unfeasible to use the traditional security approaches in these resource-constrained networks. Thus, to develop efficient security techniques, it is imperative to consider the limitations involved.

Extremely Limited Resources

Every security mechanism requires a certain amount of resources for its implementation, these resources include data memory, program memory, and energy source to power the sensor node; however, these resources are very scarce in sensor nodes.

- Memory limitations. In order to implement an efficient security mechanism, the algorithm used for such implementation must have a small footprint.
- Energy limitations. When including security mechanisms, careful attention should be paid to energy-depleting factors including the consumed energy in computation of the security functions (i.e., encrypt, decrypt, data signatures, signature verification), the consumed energy of additional security related data transmissions or overhead (i.e., initialization vectors required for encrypt/decrypt), and the energy spent in storing the security related parameters (i.e., cryptographic keys).

Highly Unreliable Communication Medium

Unreliable communication is another threat to WSN. The security relies heavily on a defined protocol, which depends on communication.

- Unreliable transfers. The packets can be corrupted or even discarded due to errors in the communication channel or to congested nodes which results in packet loss; as a consequence, application developers are forced to allocate extra resources for error handling. Most importantly is the fact that if a protocol does not have the appropriate mechanisms for error handling, packets including critical security information could be lost (e.g., a cryptographic key).
- Conflicts. Even if we had a reliable communication channel, the communication still could be unreliable due to the broadcast nature of sensor networks. If a collision occurs in the middle of a transfer, there would be conflicts and the transfer itself would fail. On a highly populated network this can be a big problem, as has already been pointed out (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002).
- Latency. Multihop routing, network congestion, and in-network processing can introduce latency to the network, making synchronization difficult between nodes. Synchronization problems can be critical for network security mechanisms that rely on error reporting and cryptographic key distribution. Some real/time communications techniques could be used in WSN (Stankovic, Abdelzaher, Lu, Sha, & Hou, 2003).

Unattended Operation

On most wireless sensor network applications, nodes are left unattended for long time periods. The three main disadvantages of leaving the network unattended are:

- Exposure to physical attacks. The network can be deployed in an environment open to adversaries, in undesirable climatologic conditions, and so forth. Thus, the probability of a node suffering a physical attack is much higher than in typical computers on traditional networks, which normally are placed on a secure location and only face attacks through the network.

- Remote management. Remote network management makes practically impossible the detection of physical attacks or network maintenance problems. The most extreme example is perhaps when a node is being used on a military battlefield reconnaissance application; in that case the node would no longer have physical contact with the user once deployed.
- No central point of administration. A sensor network must be distributed, with no central point of administration. However, if its design is not adequate, network organization would be hard, inefficient, and fragile.

Summarizing, the time the sensor network spends unattended is directly proportional to the probability of an adversary performing an attack on any of its nodes.

Security Requirements

Wireless sensor networks share many characteristics with traditional networks, including their security requirements; however, they also introduce several requirements that are exclusive to them.

Data Confidentiality

Data confidentiality is the biggest problem in network security. Every network with any security approach would probably address this issue before any other. In sensor networks, confidentiality relates to the following (Carman, Kruus, & Matt, 2000; Perrig, Szewczyk, Tygar, Wen, & Culler, 2002):

- A sensor node must not filter sensor readings to its neighbors; particularly on military applications where the stored data in a node can be highly confidential.
- On many applications, the nodes need to communicate highly confidential data (i.e., key distribution), thus, it is very important to build a secure communication channel in WSN.
- The nodes' public information, such as their identity and their public keys, can be encrypted to a certain extent for protecting against traffic analysis attacks.

The traditional approach for keeping confidential information secret is to encrypt it using a secret key that only the destination node knows, thus, resulting in confidentiality.

Data Integrity

With the implementation of confidentiality an adversary may be unable to steal any data from the sensor network. However, this does not imply that the data are secure. The adversary could still be able to modify the data to the degree of affecting the overall operation of the network. For instance, a malicious user may add or remove certain fragments to a packet. Then, this packet could be sent to its original destination. The data loss or corruption can occur even without the presence of a malicious user due to harsh environmental conditions. Thus, data integrity helps to assure that the received data have not been modified in transit.

Data Freshness

Even though data confidentiality and integrity has been achieved, we must assure that each message is fresh. Data freshness suggests that the data are recent, and assures that no old message has been resent. This requirement is especially important when shared keys strategies are being used. Typically, shared keys need to be renewed over time. However, it takes time to propagate the new keys through the entire network. Under this scheme, it would be easy for an adversary to perpetrate a packet replay attack. Furthermore, it would be easy to corrupt the operation of the network if the nodes are not well informed of the time at which the key will change. To solve this problem, a time dependent counter may be added to the packet for assuring data freshness.

Authentication

Besides modifying packets, an adversary can also potentially alter the flow of the packets through

the addition of fake packets to the network. Consequently, the adversary can make receiving node believe that the data comes from an authentic source. Additionally, authentication is needed for several administrative tasks (i.e., dynamic network reprogramming, controlling node duty cycle). Thus, we can determine that message authentication is important for many sensor network applications.

Availability

Adjusting current traditional encryption algorithms to sensor network implies an additional cost. Some approaches suggest modifying code to favor code reutilization as much as possible. Other approaches tend to use additional communication to achieve the same goal. Other more radical approaches impose restrictions to the data or propose less robust schemes (like centralized schemes) to simplify algorithms. But all of these approaches decrease the level of availability of the nodes and consequently, the availability of the entire network for the following reasons:

- The introduction of additional processing results in additional power consumption. If we exhaust the available energy of a node, its data would no longer be available.
- Introducing additional communication operations also consumes more energy. Furthermore, adding more communication considerably increases the probability of generating a collision.
- If we introduce a centralized scheme, it would only have a single point, which can be a constant threat to the availability of the entire network.

The implementation of security mechanisms not only interferes with network operation, it also can considerably affect availability of the entire network.

Autoconfiguration

WSN are an extreme case of ad hoc networks, which require that each node be independent and flexible for configuring itself according to several situations. There is no fixed infrastructure to administer a sensor network. This also brings a great challenge for security in this type of networks. For instance, the dynamic nature of the network suggest of preinstalling a key shared between the base station and the rest of the nodes (Eschenauer & Gligor, 2002). Several schemes of random key distribution have been proposed in the context of symmetric encryption techniques (Chan, Perrig, & Song, 2003; Eschenauer & Gligor, 2002; Hwang & Kim, 2004; Liu, Li, & Ning, 2005). In the area of public key cryptography on wireless sensor networks, this same dynamicity requires efficient mechanisms for key distribution. WSN must autoconfigure for key management and for establishing trust relationships among nodes, in a similar way as they autoconfigure to perform multihop routing.

If a sensor network lacks of autoconfiguration, the damage done by an adversary or even by the hostile environment could be fatal.

Security Attacks on Wireless Sensor Networks

The nature of the WSN makes them vulnerable to several types of attacks. Such attacks can be perpetrated in a variety of ways, most notably are the denial or service attacks (DoS), but there are also traffic analysis attacks, eavesdropping, physical attacks, and others. DoS attacks in wireless sensor networks go from simple communication channel saturation techniques to more sophisticated designed to tamper with the message authentication code (MAC) layer protocol (Perrig, Stankovic, & Wagner, 2004).

Due to the great differences in available energy and computational power, protecting against a well designed denial-of-service attack is practically impossible. A more powerful node could easily block any other normal node, and consequently, prevent the sensor network from performing its function.

We can observe that attacks on sensor networks are not exclusively restricted to denial-of-service attacks; among these other types of attacks we can

include compromised nodes, attacks to routing protocols, and physical attacks.

Attack Scenario

To propose and develop efficient prevention and recuperation mechanisms for attacks on wireless sensor networks it is important to know and understand the nature of the potential adversaries; these can be classified in two groups (Karlof &Wagner, 2003): mote class adversaries and laptop class adversaries. In the first case, the adversary has access to sensor nodes. In contrast, the laptop class adversary has access to more powerful devices such as personal computers, PDAs, and so forth. Thus, in this case, the devices have many advantages over legit nodes: larger energy source, more powerful processors, and they could also have high-power transmitters or a highly sensitive antenna to eavesdrop on traffic.

A laptop class adversary can produce more damage as opposed to an adversary that only has access to a few sensor nodes. For instance, a sensor node can only block radio links in a small neighborhood while an adversary with a laptop computer could block the entire sensor network with the help of a more powerful transmitter. Furthermore, a laptop class adversary could potentially eavesdrop on the traffic of the entire network, while a mote class adversary could only eavesdrop on the traffic in a very limited area.

Another commonly used adversary classification considers external and internal adversaries. Previously, we discussed external attacks, where the adversaries do not have any access to the sensor network. Conversely, internal attacks are those perpetrated by an authorized participant in the network that has turned malicious. Internal attacks can be mounted from compromised nodes that are executing malicious codes or from laptop computers that have access to cryptographic materials, data, and codes from authorized nodes.

Attacks to Routing Protocols

Most routing protocols for WSN are very simple; due to this simplicity, they are generally more vulnerable to attacks than their counterparts in ad hoc networks. Most attacks on network layer protocols fall into one of the following categories:

- Spoofed, altered, or replayed routing information. This attack is directed toward the routing information that is exchanged between nodes. By spoofing, altering, or replaying routing information, the adversaries could potentially create routing loops, attract or repel network traffic, lengthen or shorten routes, generate fake error messages, partition the network, increase node to node latency, and so forth.
- Selective forwarding. Multihop networks often operate assuming faithfully that messages will be received by their destination. On a selective forwarding attack, malicious nodes could prevent forwarding certain messages or even discard them; consequently, these messages would not propagate through the network. A simple form of this attack is very easy to be detected because the neighbor nodes could easily infer that the route is no longer valid and use an alternate one. A more subtle form of this attack is when and adversary selectively forwards packets. Therefore, if an adversary is interested in suppressing or modifying packets that come from certain source, the adversary could selectively forward the rest of the traffic, thus, the adversary would not raise any suspicion of the attack.
- Sinkhole attacks. In a sinkhole attack, the goal of the adversary is to attract all the traffic to a certain area or the network through a compromised node, creating a sinkhole (metaphorically speaking). Due to the fact that the nodes that are located across the route have the ability to alter application data, the sinkhole attacks could facilitate other types of attacks (like selective forwarding for instance).
- Sybil attacks. In a Sybil attack (Douceur, 2002), a node presents multiple identities to the rest of the nodes. Sybil attacks are a threat to geographical routing protocols, since they require the exchange of coordinates for effi-

cient packet routing. Ideally, we would expect that a node only sends a set of coordinates, but under a Sybil attack, an adversary could pretend to be in many places at once.

- Wormhole attacks. In a wormhole attack (Hu, Perrig, & Johnson, 2002) an adversary builds a virtual tunnel through a low latency link that takes the messages from one part of the network and forwards them to another. The simplest case of this attack is when one node is located between two other nodes that are forwarding. However, wormhole attacks commonly involve two distant nodes that are colluded to underestimate the distance between them and forward packets through an external communication channel that is only available to the adversary.
- HELLO flood attacks. Some protocols require nodes to send HELLO packets to advertise themselves to their neighbors. If a node receives such packet, it would assume that it is inside the RF range of the node that sent that packet. However, this assumption could be false because a laptop class adversary could easily send these packets with enough power to convince all the network nodes that the adversary is their neighbor. Consequently, nodes close to the adversary may try to use the adversary as a route to the base station, while nodes further away would send packets directly to the adversary. But the transmission power of those nodes is much less that the adversary's, thus, the packets would get lost, and that would create a state of confusion in the sensor network.
- Acknowledgement spoofing. Some routing algorithms require the use of acknowledgement signals (ACK). In this case, an adversary could spoof this signal in response to the packets that the adversary listens to. This results in convincing the transmitting node that a weak link is strong. Thus, an adversary could perform a selective forwarding attack after spoofing ACK signals to the node that the adversary intends to attack.

Attacks to Data Aggregation Techniques

Data aggregation in wireless sensor networks can significantly reduce communication overhead compared to all the nodes sending their data to the base station. However, data aggregation complicates even more network security. This is due to the fact that every intermediate node could potentially modify, forge, or discard messages. Therefore, a single compromised node could be able to alter the final aggregation value. Intruder node and compromised node attacks are two major threats to security in sensor networks that use data aggregation techniques.

Physical Attacks

Sensor networks often operate in hostile environments. In those environments, the size of the nodes plus the unattended operation mode contributes to make them very vulnerable to physical attacks (i.e., node destruction) (Wang, Gu, Schosek, Chellappan, & Xuan, 2005c). In contrast to other types of attacks, physical attacks destroy the nodes permanently, thus, their loss is irreversible. For instance, an adversary could extract cryptographic keys, alter the node's circuitry, and reprogram it or replace it with malicious nodes (Wang, Gu, Chellappan, Xuan, & Lai, 2005b). Previous work shows that a Berkeley MICA2 mote (one of the most commonly used in the research community) can be compromised in less than a minute. Even though these results are not surprising, because MICA2 motes do not have any physical protection mechanism, they give us a good idea of what a well-trained adversary can do.

Defense Countermeasures

In this section we will present some security mechanisms that have been proposed in the literature and that help in meeting the security requirements discussed earlier. For this purpose, we will begin by discussing the key establishment process in WSN which is the base for security in this type of networks. We will follow that with a

description of security mechanisms for preventing denial-of-service attacks, defense against routing protocol attacks, how to protect from traffic analysis attacks, defending against sensor node privacy attacks, and protection against physical and data aggregation attacks.

Key Establishment Process

One important aspect of security that has received a great deal of attention from the research community is the key establishment process in WSN. Due to the fact that encryption and key establishment are crucial elements in security defense mechanisms, and most security mechanisms rely on pure encryption, we will give a general overview on encryption before going into any details about specific security defense mechanisms.

Overview

The key establishment and key management problems are not exclusive to sensor networks. In fact, this type of problems has been thoroughly studied in the wireless network community. Traditionally, key establishment is performed through some public key protocol. The most commonly used is Diffie-Hellman (Diffie & Hellman, 1976), but there are many more.

However, most of the traditional techniques are not suitable for low-power devices such as sensor nodes. This is due to the fact that these techniques use asymmetric cryptography, which is also known as public key cryptography. In this case it is required to maintain two mathematically related keys, one of which is public while keeping the other private. The problem with public key cryptography in WSN

Table 1. A summary of the analysis for cipher performance (Law et al. 2004)

By key setup						
Rank	***Size Optimized***			***Speed Optimized***		
	Code mem.	***Data mem.***	***Speed***	***Code mem.***	***Data mem.***	***Speed***
1	RC5-32	MISTY1	MISTY1	RC6-32	MISTY1	MISTY1
2	KASUMI	Rijndael	Rijndael	KASUMI	Rijndael	Rijndael
3	RC6-32	KASUMI	KASUMI	RC5-32	KASUMI	KASUMI
4	MISTY1	RC6-32	Camellia	MISTY1	RC6-32	Camellia
5	Rijndael	RC5-32	RC5-32	Rijndael	Camellia	RC5-32
6	Camellia	Camellia	RC6-32	Camellia	RC5-32	RC6-32
By encryption mode						
Rank	***Size Optimized***			***Speed Optimized***		
	Code mem.	***Data mem.***	***Speed***	***Code mem.***	***Data mem.***	***Speed***
1	RC5-32	RC5-32	Rijndael	RC6-32	RC5-32	Rijndael
2	RC6-32	MISTY1	MISTY1	RC5-32	MISTY1	Camellia
3	MISTY1	KASUMI	KASUMI	MISTY1	KASUMI	MISTY1
4	KASUMI	RC6-32	Camellia	KASUMI	RC6-32	RC5-32
5	Rijndael	Rijndael	RC6-32	Rijndael	Rijndael	KASUMI
6	Camellia	Camellia	RC5-32	Camellia	Camellia	RC6-32

is that, computationally speaking, it is very heavy for the sensor nodes. However, there has been work that shows that implementation is viable if a proper selection of algorithms is made (Gaubatz, Kaps, & Sunar 2004; Gura, Patel, Wander, Eberle, & Shantz, 2004; Malan, Welsh, & Smith, 2004; Watro, Kong, Fen Cuti, Gardiner, Lynn, & Kruus, 2004).

For these reasons, symmetric encryption is the more widely selected technique for applications that cannot handle the computational complexity of asymmetric encryption. Symmetric techniques use a single key that is shared by the two communicating parties. This key is used for data encryption and decryption. The traditional example of symmetric encryption is the DES (data encryption standard) algorithm. However, the use of DES has decreased significantly because it can be easily broken. Currently, other algorithms such as 3DES (triple DES), RC5, AES, and others (Schneier, 1996).

An analysis of several cipher algorithms (Law, Doumen, & Hartel, 2004) is summarized in Table I, where two classifications are made: one by key setup and the other by encryption mode. In both classifications the algorithms were optimized for code size and speed and aspects such as speed, code size, and required data memory were evaluated.

A great challenge for symmetric encryption is the problem of key management. The problem resides in the fact that both parties need to know the key prior to starting secure communication. Thus, the problem can be summarized as follows: how can we assure that only the two communicating parties know the key and no one else does? Distributing secret keys is not an easy problem to solve because preinstalling the key in the sensor node is not always an option.

Key Establishment Protocols

There are several random key predistribution techniques that have been proposed. Eschenauer and Gligor (2002) propose a scheme based on probabilistic key sharing among sensor nodes. This scheme operates first by distributing a key chain to all participant nodes before their deployment. Each key chain consists of a set of keys that has been randomly selected from a larger offline-generated key set. To use the random key predistribution technique it is not necessary that each pair of nodes share a key. However, every pair of nodes that does share a key may use that key to establish a direct secure connection between them. Eschenauer and Gligor (2002) show that under this scheme it is highly probable that sensor nodes can operate with shared keys.

The LEAP protocol (Zhu, Setia, & Jajodia, 2003) adopts the approach of using multiple techniques for key establishment. Here, the authors make the observation than any mechanism by itself provides security for every type of connection in wireless networks. Thus, in this work they present four different types of keys that are used depending on the communication type to be established.

In *PIKE* (Chan & Perrig, 2005), the authors describe a mechanism for establishing a key between two nodes based on the trust that both nodes have toward a third node in the same network. The shared keys of each node are propagated throughout the network in such a way that for every node A and B a node C exists that shares a key with A and B. Thus, the key establishment protocol between A and B can be securely routed through C.

Perrig et al. (2002) propose a key distribution scheme for secure broadcast authentification named μTESLA. The main idea of μTESLA is to achieve asymmetric cryptography through the delayed disclosure of symmetric keys.

It is important to point out that the most significant advances in the integration of public cryptography to WSN (which will be discussed next) have been made recently. This makes random key predistribution a less interesting topic.

Public Key Cryptography

Two of the more commonly used public key cryptography algorithms are RSA and ECC (Schneier, 1996). Traditionally, it was thought that these techniques were way too complex for applying them to WSN. However, successful implementations of public key cryptographic systems in WSN have been published recently.

Gura et al. (2004) report that it is possible to implement RSA and ECC in 8-bit microprocessors, demonstrating a performance advantage of ECC over RSA. Another advantage is that the 160-bit

key in ECC generates shorter messages during transmission compared to the 1024-bit key of RSA. Particularly, this work demonstrates that the dot product operations used in ECC execute faster than the operations in RSA.

Watro et al. (2004) show that certain parts of the RSA cipher can be implemented on current sensor network platforms, particularly in the MICA2 Berkeley motes (Hill, Szewczyk, Woo, Hollar, Culler, & Pister, 2000). They implemented the public key operations in the sensor nodes while the private ones were performed in more powerful devices. In this case they used a laptop computer.

Malan et al. (2004) propose a scheme based on ECC and show an implementation of the Diffie-Hellman algorithm based on the elliptic curve discrete logarithm problem. While key generation is by no means fast (around 34 seconds for generating the pair of keys and another 34 seconds for generating the secret key), this probably would suffice for applications that do not require frequent key renewal.

Preventing Against Denial-of-Service

In Table 2 we show the most common denial of service attacks and their corresponding countermeasures classified by layers. Due to the fact that DoS attacks are very common, efficient countermeasures mechanisms are required. One approach to defend against the classic channel jamming attack is to identify the part of the network that is jammed and route traffic around that area. Wood and Stankovic (2002) describe a two phase approach where nodes along the perimeter of the jammed area report their status to their neighbors who then collaboratively define the jammed region and simply route around it.

To protect against jamming at the MAC layer, nodes could use an admission control mechanism that limits their transmission rate. This would allow the network to ignore the requests designed to exhaust the node's energy source. However, this is not an optimal solution because the network must be able to handle large volumes of traffic.

To protect against malicious nodes that intentionally misroute traffic could be done at the cost of redundancy. In this case, a node can send the message through multiple routes, thus increasing the probability that the message will arrive to its final destination simply because the message does not rely on a single route to get there.

Defending Against Routing Protocol Attacks

Routing protocols for WSN has been a well studied topic to a certain extent. However, most of the research efforts focus mainly in providing energy

Table 2. Wireless sensor network DoS attacks/defenses

Layer	*Attacks*	*Defenses*
Physical	Jamming	Spread-spectrum, priority messaging, lower duty cycle, region mapping, mode change
	Tampering	Tamper-proof, hiding
Link	Collision	Error correcting code
	Exhaustion	Rate limitation
	Unfairness	Small frames
Network (routing)	Neglect and greed	Redundancy, probing
	Homing	Encryption
	Misdirection	Egress filtering, authorization monitoring
	Black holes	Authorization, monitoring, redundancy
Transport	Flooding	Client puzzles
	Desynchronization	Authentication

efficient routing mechanisms. There is a large demand of routing protocols that besides offering energy efficiency they also offer security against certain network attacks such as sinkhole attacks, wormholes attacks, and the Sybil attack. As the WSN range of applications is increasing as well as its network densities, secure routing will be a design factor that must be considered for future applications.

Security Techniques for Routing Protocols

Deng, Han, and Mishra (2002) introduce an INtrusion tolerant routing protocol for sensor networks (INSENS). This protocol is based on minimizing the damage caused by an intruder and keep routing despite its presence, without having to identify the intruder. In this work, the authors state that an intruder does not have to be a malicious node necessarily, it very well could be a node that is just malfunctioning for physical reasons. Identifying a malicious node from a malfunctioning one could be extremely difficult. For this reason they make no distinction between them. The first technique that they propose is to mitigate the damage caused by a potential intruder by applying redundancy. This is, as we previously mentioned, sending a packet through multiple routes.

They also assume that there are large differences in available resources between the base station and the sensor nodes, thus, they propose that routing table computation is to be performed at the base station. This is done in three phases. In the first phase the base station broadcast a request that propagates through the entire network. On the next phase, the base station collects information about node connectivity. Finally, the base station computes a series of routing tables for each node. These tables include redundant routing information used for the redundant message transmission we discussed earlier.

There are several attacks that could be launched to the routing protocol during each one of the three phases. On the first phase, a node could spoof a request done by the base station. A malicious node could forward the request through a fake route or simply not forward the request done by the base station.

To avoid this, Deng et al. (2002) use a technique similar to μTESLA where one-way key chains are used to authenticate the message from the base station.

Tanachaiwiwat, Dave, Bhindwale, and Helmy (2003) introduce a novel technique that they called TRANS (trust routing for location aware networked sensors). This routing protocol was proposed for data-centric networks. It also uses delayed key disclosure to achieve asymmetric cryptography. In their implementation, they use μTESLA for message authentication and confidentiality. By using μTESLA, TRANS can be sure that a message follows a trusted route through location-based routing. The approach consists of the base station sending an encrypted broadcast message to its neighbors. Only those trusted neighbors would have the key required to decrypt that message. The trusted neighbors would add their location to the route (for returning messages), and would encrypt the message now with their own keys and send the message to the neighbor closest to the destination. When the message arrives to its destination, the receiving node must authenticate the source (in this case the base station) using a MAC that belongs to the base station. Afterwards, the node can simply send a message to the base station through the trusted route that the original message followed.

An important challenge in the area of secure routing for wireless networks is that it is very easy to disrupt the routing protocol by simply disrupting the route discovery process. Papadimitratos and Haas (2002) propose a secure route discovery protocol that guarantees, under certain conditions, that the correct network topology would be obtained. This protocol is very similar to TRANS. The security relies on the MAC layer and in an accumulation on the node identities that are included in the route. By doing this, a source node can discover the network topology because each node from the source to the destination appends its identity to the message. In order to ensure that the message has not been tampered with, a MAC code is also appended to the message, which can

be authenticated by either the destination or by the source (for returning messages).

How to Protect from Traffic Analysis Attacks

There are some strategies to protect from traffic analysis attacks. Deng, Han, and Mishra (2004) propose a technique based on a random walk through the network. This technique also send packets randomly to nodes different from the parent node in the routing tree. The main goal of this technique is to make it harder to a potential adversary to infer the route from a given node to the base station and also to prevent against a possible rate monitoring attack, but it would not protect against a time correlation attack. To protect against a time correlation attack, they propose a fractal strategy. With this technique a node would generate a fake packet (with certain probability) while one of its neighbors is sending a packet to the base station. The fake packet would be sent to another neighbor that consequently may send another fake packet, thus, deceiving the potential adversary. These fake packets would use the time-to-live (TTL) parameter to decide for how long they would be circulating throughout the network.

Defending Against Sensor Node Privacy Attacks

To protect against privacy attacks, several proposals have been made that reduce the effects of those attacks, we will discuss some of those proposals in this section (Gruteser, Schelle, Jain, Han, & Grunwald, 2003).

Anonymity Mechanisms

When very precise location information is being used it is easy to identify the user and monitor the user's activity, thus, this opens the door for a privacy attack. The anonymity mechanisms depersonalize the data before releasing them; these techniques are an alternative approach to policy-based access control.

Some researchers have proposed certain techniques that make use of anonymity mechanisms. For instance, Gruteser and Grunwald (2003a) analyze the feasibility of anonymizing location information for location-based services in an automotive telematic environment. Beresford and Stajano (2003) evaluate anonymity techniques for an indoor location-based system based on the active nat.

Producing total anonymity is a difficult problem given the lack of knowledge about the concerning node's location. Therefore, for the privacy problem, there is a tradeoff between the required anonymity level and the need for public information. Three approaches have been proposed to address this problem (Gruteser & Grunwald, 2003b; Gruteser et al., 2003; Priyantha, Chakraborty, & Balakrishnan, 2000; Smailagic & Kogan, 2002):

- Decentralize sensitive data. The main idea in this approach is to distribute the sensed location data through a spanning tree. By doing so, no single node will contain the original data.
- Secure the communication channel. By using secure communication protocols such as SPINS (Perrig et al., 2002), eavesdropping and active attacks can be prevented.
- Node mobility. Making the nodes move can be an effective defense mechanism against privacy attacks, particularly due to the fact that location information would be changing constantly. For instance, the Cricket system (Priyantha et al., 2000) is a system with location support for mobile object inside buildings.

Policy-Based Approach

The policy-based approach is a topic that is currently receiving a great deal of attention from the research community. Access control decisions and authentication are based on the specifications provided by the privacy policies. Molnar and Wagner (2004) introduce the concept of private authentication in RFID applications, which can be considered passive nodes. In the automotive

telematics domain, Duri, Gruteser, Liu, Moskowitz, Perez, Singh et al. (2002) propose a policy-based framework to protect data from the sensors, where an on-board computer can act as a trusted agent. Snekkenes (2001) presents advanced concepts for policy specification on cell phone networks. These concepts allow access control based on criteria such as request time, location, object speed, and identity. Myles, Friday and Davies (2003) describe an architecture for a centralized server that controls the access of client applications through the use of validation modules that verify the XML-formatted application policies. Hengartner and Steenkiste (2003) point out that access control policies must be governed by room or user policies. The room policies specify who is authorized to find out about the people currently in the room, while user policies state who is permitted to access location information about another user.

Langheinrich (2005) proposed a framework called PawS (privacy awareness system). This framework is based on privacy policy advertisements through special packets called privacy beacons. Those policies are maintained with privacy proxies, which keep databases that store those policies.

Information Flooding

Ozturk, Zhang, Trappe, and Ott (2004) propose antitraffic analysis mechanisms to prevent an external adversary from obtaining the location of a data source. Random data routing and phantom traffic are used to hide real traffic, so that it is difficult for an adversary to track the data source through traffic analysis. Ozturk et al. have developed comparable methods that rely on flooding-based routing protocols.

Some similar mechanisms can be used to prevent an adversary to track the base station through traffic analysis (Gura et al., 2004). A key problem with these techniques is that they involve an energy cost in order to provide information anonymity.

Protecting from Physical Attacks

Physical attacks, as we pointed out earlier, represent an important threat to sensor networks because of their unattended operation mode and their extremely limited resources. Nodes may be equipped with tamper-proof physical protection. For instance, an alternative to this is tamper-proof packaging (Wood & Stankovic, 2002). Related research work focuses in the design of hardware that make their memory content inaccessible to adversaries. Another alternative is to use special software and hardware to detect physical tampering.

As the hardware costs decrease, integrating tamper-proof hardware would be a feasible solution for sensor network applications. However, the research community has agreed by consensus that the trend should be making cheaper sensor nodes without adding extra functionalities; thus, integrating physical protection is not a solution that would be commonly accepted in the near future. One possible approach for protecting against physical attacks is self-destruction. The main idea behind this approach is that whenever a node detects a possible attack it self-destructs. This is particularly feasible on networks where there are redundant nodes and when the cost per node is low. Obviously, the key to this approach is detecting a possible attack. One possible solution is to statically verify the status of their neighbors, but in mobile networks this still is an open problem.

Regarding the deployment of security components outside the nodes, several proposals have been made (Bulusu & Jha, 2005). Sastry, Shankar, and Wagner (2003) introduce the concept of secure location verification and propose a secure localization scheme called ECHO that assures node location legitimacy. In this scheme, the security relies over physical sound properties and RF. The adversary cannot claim to have a shorter distance by starting the ultrasound response early because it will not have the nonce.

Hu and Evans (2004) use directional antennas to defend against wormhole attacks. In the work presented by Wang et al. (2005b) the authors study the modeling and defense of sensor networks against search-based physical attacks. They define a physical attack-based model, where an adversary walks the network using signal detecting equipment to locate active nodes and destroy them. In prior work, the authors identified and modeled blind physical attacks (Wang, Gu, Chellappan,

Schosek, & Xuan, 2005a). The defense algorithm is executed by individual nodes in two phases: in the first phase, the nodes detect the attacker and notify other nodes; in the second phase, the nodes receive the notification and change their state to safe mode.

Seshadri, Perrig, Van Doorn, and Khosla (2004) introduce a mechanism called SWATT to verify and detect when memory content is altered. This mechanism can be use as defense against a physical attack by modifying code in the nodes.

Secure Data Aggregation

As sensor networks increase in size, the amount of data that they collectively sense also increases. However, due to the computational limitations of each node, a small sensor is only responsible for a very small portion of the entire data. Due do this, a network search would probably return a large amount of raw data, most of which would not be of the user's interest.

For this reason, raw data preprocessing is recommended to produce more meaningful results to the user. This is typically done by a series of aggregators. An aggregator is responsible for collecting raw data from a subset of nodes and processing that raw data into more usable data.

However, aggregation techniques are particularly vulnerable to attacks because a single aggregator node is responsible for processing the data from multiple nodes. Due to this fact, secure data aggregation techniques are required by sensor network that consider the possibility of one or more malicious nodes.

Overview

If an aggregator node is compromised, then all the transmitted data in the network to the base station may be forged. To detect this, Ye, Luo, Lu, and Zhang (2005) define a mechanism based on statistical filters. This uses multiple MAC codes across the entire route from the aggregator node to the base station. Any packet that does not pass verification would be discarded.

Wagner (2004) analyzes the resiliency of aggregation techniques, and argues that current aggregation techniques were proposed without security in mind, and thus, are vulnerable to attacks. A mathematical framework is proposed to formally evaluate security for aggregation. This theory allows quantifying the robustness of an aggregation operation against a malicious attack. By using the framework, it is argued that the aggregation functionalities that can be securely computed under the presence of k compromised nodes are exactly the functions that are (k, α)-resilient for some α that is not too large. This work opened the door for secure data aggregation in sensor networks. However, the presented level of aggregation model is fairly simple compared to real sensor network implementations. Extending this technique to multilevel aggregation scenarios with heterogeneous devices is an interesting challenge.

Secure Data Aggregation Techniques

As we pointed out earlier, data aggregation has been studied in reasonable depth. The problem with classical data aggregation is that they all assume trusted nodes. Of course, in practice this may not be the case, and for this reason, secure data aggregation techniques are required.

Przydatek, Song, and Perrig (2003) describe a secure information aggregation (SIA). They point out that aggregation techniques and sensor networks are vulnerable to a variety of attacks including denial-of-service attacks. However, this work focuses on protecting against a specific type of attack called stealthy attack. The goal of SIA is to ensure that if a user accepts the result of an aggregation as correct, then there is a high probability that the value is close to the true aggregation value. In case that the aggregated value has been tampered with, the user must reject the forged value with a high probability.

Hu and Evans (2003) propose a secure aggregation technique that uses the μTESLA protocol to provide security. In this case, the nodes organize into a hierarchy tree where intermediate nodes play the aggregator role. Recall that the μTESLA achieves asymmetry through delayed disclosure of symmetric keys. For this, a child cannot verify the data authenticity immediately because the key used to generate the MAC code has not been disclosed.

However, this technique does not guarantee that the data being reported by the nodes and the aggregator are correct. To address this problem, the base station is responsible for distributing temporary keys to the network as well as the μTESLA key used for validating the MAC. By using this key, the node can verify their children's MAC codes.

We can note that secure data aggregation techniques play an important role in adopting WSN technology due to the large amount of raw data and the localized in-network processing required in these networks. Research efforts in this area have been limited, thus, much more investigation is needed in this particular topic.

CONCLUSION

Certainly, incorporating efficient security mechanisms to WSN is a huge challenge, mainly because of the differences they have compared to traditional networks. Their resource constraints, their large scale deployments, along with their operating environments, represent great obstacles to achieve security. Nevertheless, efficient mechanisms have been proposed to deal with a great variety of attacks to which WSN presumably are subjected to. These security techniques confront specific attacks that operate across different layers of the protocol stack. Attacks like signal jamming (physical layer), induced collisions (MAC sublayer), packet redirection (routing layer), and many others have been the addressed through many security mechanisms, many of which we described in this chapter.

However, most of the security techniques rely heavily on a key distribution protocol and assume that secret keys have already been placed on the distributed nodes. However as we showed in this chapter, efficient key distribution in WSN is no easy task. In fact, most of the research efforts in WSN security are directed to proposing efficient key distribution techniques; in this chapter we discussed research work in the area of WSN key distribution. As of now, we still believe that there is much room for improvement in efficient key distribution in wireless sensor networks. As more efficient key distribution key mechanisms continue to appear, more efficient application-specific security techniques will also emerge.

But overall, perhaps the biggest challenge of all is proving that the proposed security techniques work well in real-world sensor network applications. Currently, there is a huge gap between real-world WSN development and WSN security research. Thus, we consider that integrating the proposed security techniques to real-world applications is a challenge that should be faced in the near future, as opposed to proposing new techniques that most of the time does not go beyond lab implementations.

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KEY TERMS

Compromised Node: A node on which an attacker has gained control after network deployment. Generally compromise occurs once an attacker has found a node, and then directly connects the node to their computer via a wired connection of some sort. Once connected the attacker controls the node by extracting the data and/or putting new data or controls on that node.

Data Aggregation: Process of reducing large amounts of sensor generated data to smaller and more representative data sets that synthesize the state of the phenomena that the network is monitoring.

Data Freshness: Implies that the sensed data are recent, and it ensures that no adversary replayed old messages.

Insider Attacks: These types of attacks are those launched by adversaries that have access to one or more compromised nodes in a network. Insider attacks are the most challenging ones because the adversary has access to the network's cryptographic materials (i.e., keys, ciphers, and data).

Key Distribution: Process of efficiently distributing cryptographic keys to the nodes that belong to a network. These keys could either be pairwise keys (for two party communications), group keys (for cluster-wide communication), or network keys (for secure broadcast communication).

Mote: A wireless receiver/transmitter that is typically combined with a sensor of some type to create a remote sensor. Some motes are designed to be incredibly small so that they can be deployed by the hundreds or even thousands for various applications

Node Authentication: Process of ensuring that a given node and its data are legit.

Outsider Attacks: Attacks perpetrated by adversaries that do not have access to direct access to any of the authorized nodes in the network. However, the adversary may have access to the physical medium, particularly if we are dealing with wireless networks. Therefore, attacks such as replay messages and eavesdropping fall into this classification. However, coping with this attack is fairly easy by using traditional security techniques such as encryption and digital signatures.

Chapter XXXV
Security and Privacy in Wireless Sensor Networks:
Challenges and Solutions

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ABSTRACT

The applications of wireless sensor networks (WSNs) are continuously expanding. Recently, consistent research and development activities have been associated to this field. Security ranks at the top of the issues that should be discussed when deploying a WSN. This is basically due to the fact that WSNs are, by nature, mission-critical. Their applications mainly include battlefield control, emergency response (when a natural disaster occurs), and healthcare. This chapter reviews recent research results in the field of WSN security.

INTRODUCTION

The applications of wireless sensor networks (WSNs), which cover both the civil and military contexts, are continuously expanding. The ability to develop miniaturized, battery powered motes that combine sensing, correlation, fusion, and wireless communication capabilities makes the WSN technology cost-effective for being used in future. In fact, WSNs can be used to gather and analyze information about vehicular movement, humidity, temperature, pressure, as well as many other parameters.

However, the enormous potential of WSNs can be unlocked only if the corresponding infrastructures are adequately safeguarded. In fact, violating one or more security properties would lead to wrong decisions, and consequently wrong reactions. Hence, security should rank at the top of the issues that should be discussed when designing a WSN. Another motivation is that WSNs are, by nature, mission-critical, meaning that they are developed for sensitive tasks where error-tolerance is very small. The importance of security in the WSN context is exacerbated by certain factors including the following:

- Sensor nodes have limited storage, computation, and power resources. For this reason, security mechanisms should be adapted to the WSN capabilities.
- The network does not have a static infrastructure. WSN architectures can be only timely defined. This renders the application of existing robust cryptographic mechanisms (e.g., public key infrastructure [PKI], digital signature) more difficult than in customary networks.
- The sensing and communication tasks are often performed in a hostile environment where the gathered events are subjected to numerous threats that might affect the final decision.
- The detected events are forwarded through the sensor nodes themselves, preventing the application of strong communication security mechanisms.

This chapter surveys recent research activities in the area of WSN security. More accurately, the following aspects will be discussed:

1. **Wireless sensor networks:** This section addresses several WSN basic issues to highlight the related scientific challenges. Components, architecture, topology, routing, mobile target tracking, and alert management will be, among others, discussed.
2. **WSN security objectives:** Traditional security goals (i.e., confidentiality, authenticity, integrity, and availability) should be extended to fit the requirements of WSNs. Several particular concepts are introduced at this level. For instance, confidentiality, authenticity, and integrity, which have been customarily associated to data and node identity, should be extended to cover node location. This poses several new security challenges in the WSN context.
3. **Attacks against WSNs:** This section describes the most important attacks techniques concerning WSNs. Attacks are classified according to the basic security properties they violate. A taxonomy of these attacks will also be proposed. This taxonomy is based on three major attack activities: (1) attacks on transmitted information, (2) attacks on architecture, structure, protocols, and (3) attacks on the localization framework.
4. **Countermeasures:** Potential security solutions that allow countering the aforementioned threats will be proposed. They will be classified according to the level at which they act (e.g., link level, routing, and application). Countermeasures will be also categorized into preventive and reactive solutions. For example, robust localization (resp. fault-tolerance) schemes belong to the first (resp. second) category.
5. **Building security policies for WSNs:** Several key security processes, such as monitoring and incident response, can not be directly applied in the WSN field. They should therefore be heavily adapted in order to support WSN specific constraints.

WIRELESS SENSOR NETWORKS

Due to advances in wireless communications and electronics over the last few years, the development of networks of low-cost, low-power, multifunctional sensors has received increasing attention. These sensors are small in size and able to sense, process data, and communicate with each other, typically over an radio frequency (RF) channel. A sensor network is designed to detect events or phenomena, collect and process data, and transmit sensed information to interested users. Basic features of sensor networks are:

- Self-organizing capabilities
- Short-range broadcast communication and multihop routing
- Dense deployment and cooperative effort of sensor nodes
- Frequently changing topology due to fading and node failures
- Limitations in energy, transmit power, memory, and computing power

These characteristics, particularly the last three, make sensor networks different from other wireless ad hoc or mesh networks. Clearly, the idea of mesh networking is not new; it has been suggested for some time for wireless Internet access or voice communication. Similarly, small computers and sensors are not innovative per se. However, combining small sensors, low-power computers, and radios makes for a new technological platform that has numerous important uses and applications.

Wireless sensor networks are interesting from an engineering perspective, because they present a number of serious challenges that cannot be adequately addressed by existing technologies:

- **Extended lifetime:** As mentioned above, WSN nodes will generally be severely energy constrained due to the limitations of batteries. A typical alkaline battery, for example, provides about 50 watt-hours of energy; this may translate to less than a month of continuous operation for each node in full active mode. Given the expense and potential infeasibility of monitoring and replacing batteries for a large network, much longer lifetimes are desired. In practice, it will be necessary in many applications to provide guarantees that a network of unattended wireless sensors can remain operational without any replacements for several years.
- **Responsiveness:** A simple solution to extending network lifetime is to operate the nodes in a duty-cycled manner with periodic switching between sleep and wake-up modes. While synchronization of such sleep schedules is challenging in itself, a larger concern is that arbitrarily long sleep periods can reduce the responsiveness and effectiveness of the sensors. In applications where it is critical that certain events in the environment be detected and reported rapidly, the latency induced by sleep schedules must be kept within strict bounds, even in the presence of network congestion.
- **Robustness:** The vision of wireless sensor networks is to provide large scale, yet fine-grained coverage. This motivates the use of large numbers of inexpensive devices. However, inexpensive devices can often be unreliable and prone to failures. Rates of device failure will also be high whenever the sensor devices are deployed in harsh or hostile environments. Protocol designs must therefore have built-in mechanisms to provide robustness. It is important to ensure that the global performance of the system is not sensitive to individual device failures. Further, it is often desirable that the performance of the system degrade as gracefully as possible with respect to component failure.
- **Synergy:** Moore's law-type advances in technology have ensured that device capabilities in terms of processing power, memory, storage, radio transceiver performance, and even accuracy of sensing improve rapidly (given a fixed cost). However, if economic considerations dictate that the cost per node be reduced drastically from hundreds of dollars to less than a few cents, it is possible that the capabilities of individual nodes will remain constrained to some extent. The challenge is therefore to design synergistic protocols, which ensure that the system as a whole is more capable than the sum of the capabilities of its individual components. The protocols must provide an efficient collaborative use of storage, computation, and communication resources.
- **Scalability:** For many envisioned applications, the combination of fine granularity sensing and large coverage area implies that wireless sensor networks have the potential to be extremely large scale (tens of thousands, perhaps even millions of nodes in the long term). Protocols will have to be inherently distributed, involving localized communication, and sensor networks must utilize hierarchical architectures in order to provide such scalability. However, visions of large numbers of nodes will remain unrealized in practice until some fundamental problems, such as failure handling and in-situ reprogramming, are addressed even in small settings involving tens to hundreds of nodes.

There are also some fundamental limits on the throughput and capacity that impact the scalability of network performance.

- **Heterogeneity:** There will be a heterogeneity of device capabilities (with respect to computation, communication, and sensing) in realistic settings. This heterogeneity can have a number of important design consequences. For instance, the presence of a small number of devices of higher computational capability along with a large number of low-capability devices can dictate a two-tier, cluster-based network architecture, and the presence of multiple sensing modalities requires pertinent sensor fusion techniques. A key challenge is often to determine the right combination of heterogeneous device capabilities for a given application.
- **Self-configuration:** Because of their scale and the nature of their applications, wireless sensor networks are inherently *unattended* distributed systems. Autonomous operation of the network is therefore a key design challenge. From the very start, nodes in a wireless sensor network have to be able to configure their own network topology: localize, synchronize, and calibrate themselves, coordinate inter-node communication, and determine other important operating parameters.
- **Privacy and security:** The large scale, prevalence, and sensitivity of the information collected by wireless sensor networks (as well as their potential deployment in hostile locations) give rise to the final key challenge of ensuring both privacy and security.

WSN SECURITY OBJECTIVES

WSN Security Challenges

WSNs are characterized by many constraints compared to traditional communication networks. Due to these particular constraints, the application of existing network security approaches does not allow to fulfill the required security properties. Hence, appropriate security needs and techniques should be defined for WSN environments while borrowing concepts from the currently used security mechanisms. In the following, we highlight the most relevant, from security point of view, WSN intrinsic features.

Resource Limitations

Security mechanisms and processes necessarily require a certain amount of processing, power, storage, and memory resources. However, sensor nodes are often resource-impoverished. In the following, we detail the basic resource limitations characterizing WSNs.

- **Processing limitations:** A custom processor for sensor nodes should essentially have a low-power sleep mode, allowing reducing energy consumption, and a low-overhead wakeup mechanism, preventing the occurrence of network congestion due to signalling messages. Ekanayake (2004) shows that the processing speed offered by most of the available microcontrollers ranges between 4 and 400 MIPS. Even though this is a performance to implement the communication functions, it turns out to be not sufficient to support advanced security mechanisms, especially when a heavy traffic is exchanged across the WSN. For instance, it has been shown by Blaß (2005) that a traditional Diffie-Hellman key exchange operation would last 48.04 seconds on the AmtelMega processor. As a result, novel security algorithms should be considered to keep up with the sensor node processing limitations.
- **Limited memory and storage space:** A sensor is a tiny device with only a small amount of memory and storage space for the code. In order to build an effective security mechanism, it is necessary to limit the code size of the security algorithm. For example, one common sensor type (TelosB) has an 16-bit, 8 MHz RISC CPU with only 10K RAM, 48K program memory, and 1024K flash storage. With such a limitation, the software

built for the sensor must also be quite small. The total code space of TinyOS, the de-facto standard operating system for wireless sensors, is approximately 4 K (Hill 2000), and the core scheduler occupies only 178 bytes. Therefore, the code size for the all security related code must also be reduced.

- **Power limitation:** Energy is the biggest constraint to wireless sensor capabilities. We assume that once sensor nodes are deployed in a sensor network, they cannot be easily replaced (high operating cost) or recharged (high cost of sensors). Therefore, the battery charge taken with them to the field must be conserved to extend the life of the individual sensor node and the entire sensor network. When implementing a cryptographic function or protocol within a sensor node, the energy impact of the added security code must be considered. When adding security to a sensor node, we are interested in the impact that security has on the lifespan of a sensor (i.e., its battery life). The extra power consumed by sensor nodes due to security is related to the processing required for security functions (e.g., encryption, decryption, signing data, and verifying signatures), the energy required to transmit the security related data or overhead (e.g., initialization vectors needed for encryption/decryption), and the energy required to store security parameters in a secure manner (e.g., cryptographic key storage).

Data Loss

Certainly, unreliable communication is another threat to sensor security. The security of the network relies heavily on a defined protocol, which in turn depends on communication.

- **Unreliable transfer:** Normally the packet-based routing of the sensor network is connectionless and thus inherently unreliable. Packets may get damaged due to channel errors or dropped at highly congested nodes. The result is lost or missing packets. Furthermore, the unreliable wireless communication channel also results in damaged packets. A higher channel error rate also forces the software developer to devote resources to error handling. More importantly, if the protocol lacks the appropriate error handling it is possible to lose critical security packets. This may include, for example, a cryptographic key.
- **Collisions:** WSNs impose strict requirements on a medium access protocol. This is basically due to the ad hoc architecture characterizing WSNs as well as the long network lifetime needs. Moreover, as data are broadcasted over the radio link, packets may collide resulting in decreasing of the channel throughput. Depending on the medium access and transport layer protocols, the information loss can reach a certain degree such that the analysis center becomes no longer able to identify the events corresponding to the gathered data.
- **Latency:** Multihop routing, network congestion, and node processing can lead to greater latency in the network, thus making it difficult to achieve synchronization among sensor nodes. The synchronization issues can be critical to sensor security where the security mechanism relies on critical event reports and cryptographic key distribution. Interested readers please refer to Stankovic (2003) on real-time communications in wireless sensor networks.

Uncontrollable Behavior

Depending on the function of the particular sensor network, the sensor nodes may be left unattended for long periods of time. There are three main caveats to unattended sensor nodes:

- **Exposure to physical attacks:** The sensor may be deployed in an environment open to adversaries, bad weather, and so on. The likelihood that a sensor suffers a physical attack in such an environment is therefore much higher than the typical PCs, which is located in a secure place and mainly faces attacks from a network.

- **Managed remotely:** Remote management of a sensor network makes it virtually impossible to detect physical tampering (i.e., through tamperproof seals) and physical maintenance issues (e.g., battery replacement). Perhaps the most extreme example of this is a sensor node used for remote reconnaissance missions behind enemy lines. In such a case, the node may not have any physical contact with friendly forces once deployed.
- **No central management point:** A sensor network should be a distributed network without a central management point. This will increase the vitality of the sensor network. However, if designed incorrectly, it will make the network organization difficult, inefficient, and fragile.

Security Requirements

A sensor network is a special type of network. It shares some commonalities with a typical computer network, but also poses unique requirements of its own as discussed in Section 3. Therefore, we can think of the requirements of a wireless sensor network as encompassing both the typical network requirements and the unique requirements suited solely to wireless sensor networks.

Data Confidentiality

Data confidentiality is the most important issue in network security. Every network with any security focus will typically address this problem first. In sensor networks, the confidentiality relates to the following (Carman 2000; Perrig 2002):

- A sensor network should not leak sensor readings to its neighbors. Especially in a military application, the data stored in the sensor node may be highly sensitive.
- In many applications nodes communicate highly sensitive data, for example, key distribution; therefore it is extremely important to build a secure channel in a wireless sensor network.
- Public sensor information, such as sensor identities and public keys, should also be encrypted to some extent to protect against traffic analysis attacks.

The standard approach for keeping sensitive data secret is to encrypt the data with a secret key that only intended receivers possess, thus achieving confidentiality.

Data Integrity

With the implementation of confidentiality, an adversary may be unable to steal information. However, this does not mean the data are safe. The adversary can change the data, so as to send the sensor network into disarray. For example, a malicious node may add some fragments or manipulate the data within a packet. This new packet can then be sent to the original receiver. Data loss or damage can even occur without the presence of a malicious node due to the harsh communication environment. Thus, data integrity ensures that any received data have not been altered in transit.

Data Freshness

Even if confidentiality and data integrity are assured, we also need to ensure the freshness of each message. Informally, data freshness suggests that the data are recent, and it ensures that no old messages have been replayed. This requirement is especially important when there are shared-key strategies employed in the design. Typically shared keys need to be changed over time. However, it takes time for new shared keys to be propagated to the entire network. In this case, it is easy for the adversary to use a replay attack. Also, it is easy to disrupt the normal work of the sensor, if the sensor is unaware of the new key change time. To solve this problem a nonce, or another time-related counter, can be added into the packet to ensure data freshness.

Availability

Adjusting the traditional encryption algorithms to fit within the wireless sensor network is not free, and will introduce some extra costs. Some approaches choose to modify the code to reuse as much code as possible. Some approaches try to make use of additional communication to achieve the same goal. What is more, some approaches force strict limitations on the data access, or propose an unsuitable scheme (such as a central point scheme) in order to simplify the algorithm. But all these approaches weaken the availability of a sensor and sensor network for the following reasons:

- Additional computation consumes additional energy. If no more energy exists, the data will no longer be available.
- Additional communication also consumes more energy. What is more, as communication increases so too does the chance of incurring a communication conflict.
- A single point failure will be introduced if using the central point scheme. This greatly threatens the availability of the network.
- The requirement of security not only affects the operation of the network, but also is highly important in maintaining the availability of the whole network.

Self-Organization

A wireless sensor network is typically an ad hoc network, which requires every sensor node be independent and flexible enough to be self-organizing and self-healing according to different situations. There is no fixed infrastructure available for the purpose of network management in a sensor network. This inherent feature brings a great challenge to wireless sensor network security as well. For example, the dynamics of the whole network inhibits the idea of preinstallation of a shared key between the base station and all sensors (Eschenauer 2002). Several random key predistribution schemes have been proposed in the context of symmetric encryption techniques (Chan 2003; Eschenauer 2002; Hwang 2004; Liu 2005). In the context of applying public-key cryptography techniques in sensor networks, an efficient mechanism for public-key distribution is necessary as well. In the same way that distributed sensor networks must self-organize to support multihop routing, they must also self-organize to conduct key management and building trust relation among sensors. If self-organization is lacking in a sensor network, the damage resulting from an attack or even the hazardous environment may be devastating.

Time Synchronization

Most sensor network applications rely on some form of time synchronization. In order to conserve power, an individual sensor's radio may be turned off for periods of time. Furthermore, sensors may wish to compute the end-to-end delay of a packet as it travels between two pair-wise sensors. A more collaborative sensor network may require group synchronization for tracking applications and so forth. Ganeriwal (2005), proposes a set of secure synchronization protocols for sender-receiver (pair-wise), multihop sender-receiver (for use when the pair of nodes are not within single-hop range), and group synchronization.

Secure Localization

Often, the utility of a sensor network will rely on its ability to accurately and automatically locate each sensor in the network. A sensor network designed to locate faults will need accurate location information in order to pinpoint the location of a fault. Unfortunately, an attacker can easily manipulate nonsecured location information by reporting false signal strengths, replaying signals, and so forth.

A technique called verifiable multilateration (VM) is described by Capkun (2006). In multilateration, a device's position is accurately computed from a series of known reference points. Capkun (2006) uses authenticated ranging and distance bounding to ensure accurate location of a node. Because of distance bounding, an attacking node can only increase its claimed distance from a

reference point. However, to ensure location consistency, an attacking node would also have to prove that its distance from another reference point is shorter. Since it cannot do this, a node manipulating the localization protocol can be found. For large sensor networks, the secure positioning for sensor networks (SPINE) algorithm is used. It is a three phase algorithm based upon verifiable multilateration.

Lazos (2005) describes secure range-independent localization (SeRLoc). Its novelty is its decentralized, range-independent nature. SeRLoc uses locators that transmit beacon information. It is assumed that the locators are trusted and cannot be compromised. Furthermore, each locator is assumed to know its own location. A sensor computes its location by listening for the beacon information sent by each locator. The beacons include the locator's location. Using all of the beacons that a sensor node detects, a node computes an approximate location based on the coordinates of the locators. Using a majority vote scheme, the sensor then computes an overlapping antenna region. The final computed location is the centroid of the overlapping antenna region. All beacons transmitted by the locators are encrypted with a shared global symmetric key that is preloaded to the sensor prior to deployment. Each sensor also shares a unique symmetric key with each locator. This key is also preloaded on each sensor.

Authentication

An adversary is not just limited to modifying the data packet. It can change the whole packet stream by injecting additional packets. So the receiver needs to ensure that the data used in any decision-making process originate from the correct source. On the other hand, when constructing the sensor network, authentication is necessary for many administrative tasks (e.g., network reprogramming or controlling sensor node duty cycle). From the above, we can see that message authentication is important for many applications in sensor networks. Informally, data authentication allows a receiver to verify that the data really are sent by the claimed sender. In the case of two-party communication, data authentication can be achieved through a purely symmetric mechanism: the sender and the receiver share a secret key to compute the message authentication code (MAC) of all communicated data.

Adrian Perrig et al. (2002) propose a key-chain distribution system for their μTESLA secure broadcast protocol. The basic idea of the μTESLA system is to achieve asymmetric cryptography by delaying the disclosure of the symmetric keys. In this case a sender will broadcast a message generated with a secret key. After a certain period of time, the sender will disclose the secret key. The receiver is responsible for buffering the packet until the secret key has been disclosed. After disclosure the receiver can authenticate the packet, provided that the packet was received before the key was disclosed. One limitation of μTESLA is that some initial information must be unicast to each sensor node before authentication of broadcast messages can begin. Liu and Ning (2003, 2004) propose an enhancement to the μTESLA system that uses broadcasting of the key chain commitments rather than μTESLA's unicasting technique. They present a series of schemes starting with a simple predetermination of key chains and finally settling on a multilevel key chain technique. The multilevel key chain scheme uses predetermination and broadcasting to achieve a scalable key distribution technique that is designed to be resistant to denial-of-service (DoS) attacks, including jamming.

Attacks against WSNs

Sensor networks are particularly vulnerable to several key types of attacks. Attacks can be performed in a variety of ways, most notably as denial-of-service attacks, but also through traffic analysis, privacy violation, physical attacks, and so on. Denial-of-service attacks on wireless sensor networks can range from simply jamming the sensor's communication channel to more sophisticated attacks designed to violate the 802.11 MAC protocol (Perrig 2004) or any other layer of the wireless sensor network.

Due to the potential asymmetry in power and computational constraints, guarding against a well

orchestrated denial-of-service attack on a wireless sensor network can be nearly impossible. A more powerful node can easily jam a sensor node and effectively prevent the sensor network from performing its intended duty. We note that attacks on wireless sensor networks are not limited to simply denial-of-service attacks, but rather encompass a variety of techniques including node takeovers, attacks on the routing protocols, and attacks on a node's physical security. In this section, we first address some common denial-of-service attacks and then describe additional attacking, including those on the routing protocols as well as an identity based attack known as the Sybil attack.

Denial-of-Service Attacks

A standard attack on wireless sensor networks is simply to jam a node or set of nodes. Jamming, in this case, is simply the transmission of a radio signal that interferes with the radio frequencies being used by the sensor network (Wood 2002). The jamming of a network can come in two forms: constant jamming and intermittent jamming. Constant jamming involves the complete jamming of the entire network. No messages are able to be sent or received. If the jamming is only intermittent, then nodes are able to exchange messages periodically, but not consistently. This too can have a detrimental impact on the sensor network as the messages being exchanged between nodes may be time sensitive. Attacks can also be made on the link layer itself. One possibility is that an attacker may simply intentionally violate the communication protocol, for example, ZigBee or IEEE 801.11b (Wi-Fi) protocol, and continually transmit messages in an attempt to generate collisions. Such collisions would require the retransmission of any packet affected by the collision. Using this technique it would be possible for an attacker to simply deplete a sensor node's power supply by forcing too many retransmissions. At the routing layer, a node may take advantage of a multihop network by simply refusing to route messages. This could be done intermittently or constantly with the net result being that any neighbor who routes through the malicious node will be unable to exchange messages with, at least, part of the network. The transport layer is also susceptible to attack, as in the case of flooding. Flooding can be as simple as sending many connection requests to a susceptible node. In this case, resources must be allocated to handle the connection request. Eventually, a node's resources will be exhausted, thus rendering the node useless.

Traffic Analysis Attacks

Wireless sensor networks are typically composed of many low-power sensors communicating with a few relatively robust and powerful base stations. It is not unusual, therefore, for data to be gathered by the individual nodes where they are ultimately routed to the base station. Often, for an adversary to effectively render the network useless, the attacker can simply disable the base station. To make matters worse, Deng et al. (2005) demonstrate two attacks that can identify the base station in a network (with high probability) without even understanding the contents of the packets (if the packets are themselves encrypted).

A rate monitoring attack simply makes use of the idea that nodes closest to the base station tend to forward more packets than those farther away from the base station. An attacker needs only to monitor which nodes are sending packets and follow those nodes that are sending the most packets. In a time correlation attack, an adversary simply generates events and monitors to whom a node sends its packets. To generate an event, the adversary could simply generate a physical event that would be monitored by the sensor(s) in the area (turning on a light, for instance).

Wormhole Attacks

In a wormhole attack, an attacker receives packets at one point in the network, "tunnels" them to another point in the network, and then replays them into the network from that point. For tunnelled distances longer than the normal wireless transmission range of a single hop, it is simple for the attacker to make the tunneled packet arrive with better metric than a normal multihop route,

for example, through use of a single long-range directional wireless link or through a direct wired link to a colluding attacker. It is also possible for the attacker to forward each bit over the wormhole directly, without waiting for an entire packet to be received before beginning to tunnel the bits of the packet, in order to minimize delay introduced by the wormhole. Due to the nature of wireless transmission, the attacker can create a wormhole even for packets not addressed to it, since it can overhear them in wireless transmission and tunnel them to the colluding attacker at the opposite end of the wormhole. If the attacker performs this tunneling honestly and reliably, no harm is done; the attacker actually provides a useful service in connecting the network more efficiently. However, the wormhole puts the attacker in a very powerful position relative to other nodes in the network, and the attacker could exploit this position in a variety of ways. The attack can also still be performed even if the network communication provides confidentiality and authenticity, and even if the attacker has no cryptographic keys. Furthermore, the attacker is invisible at higher layers; unlike a malicious node in a routing protocol, which can often easily be named, the presence of the wormhole and the two colluding attackers at either endpoint of the wormhole are not visible in the route. The wormhole attack is particularly dangerous against many ad hoc network routing protocols in which the nodes that hear a packet transmission directly from some node consider themselves to be in range of (and, thus a neighbor of) that node.

Attacks against Privacy

Sensor network technology promises a vast increase in automatic data collection capabilities through efficient deployment of tiny sensor devices. While these technologies offer great benefits to users, they also exhibit significant potential for abuse. Particularly relevant concerns are privacy problems, since sensor networks provide increased data collection capabilities (Gruteser 2003). Adversaries can use even seemingly innocuous data to derive sensitive information if they know how to correlate multiple sensor inputs. For example, in the famous "panda-hunter problem" (Ozturk 2004), the hunter can imply the position of pandas by monitoring the traffic. The main privacy problem, however, is not that sensor networks enable the collection of information. In fact, much information from sensor networks could probably be collected through direct site surveillance. Rather, sensor networks aggravate the privacy problem because they make large volumes of information easily available through remote access. Hence, adversaries need not be physically present to maintain surveillance. They can gather information in a low-risk, anonymous manner. Remote access also allows a single adversary to monitor multiple sites simultaneously (Chan 2003). Some of the more common attacks (Chan 2003; Gruteser 2003) against sensor privacy are:

- **Monitor and eavesdropping:** This is the most obvious attack to privacy. By listening to the data, the adversary could easily discover the communication contents. When the traffic conveys the control information about the sensor network configuration, which contains potentially more detailed information than accessible through the location server, the eavesdropping can act effectively against the privacy protection.
- **Traffic analysis:** Traffic analysis typically combines with monitoring and eavesdropping. An increase in the number of transmitted packets between certain nodes could signal that a specific sensor has registered activity. Through the analysis on the traffic, some sensors with special roles or activities can be effectively identified.
- **Camouflage:** Adversaries can insert their node or compromise the nodes to hide in the sensor network. After that these nodes can masquerade as a normal node to attract the packets, then misroute the packets, for example, forward the packets to the nodes conducting the privacy analysis.

Physical Attacks

Sensor networks typically operate in hostile outdoor environments. In such environments, the small form factor of the sensors, coupled with the unat-

tended and distributed nature of their deployment, make them highly susceptible to physical attacks, that is, threats due to physical node destructions (Wang 2004).

Unlike many other attacks mentioned above, physical attacks destroy sensors permanently, so the losses are irreversible. For instance, attackers can extract cryptographic secrets, tamper with the associated circuitry, modify programming in the sensors, or replace them with malicious sensors under the control of the attacker (Wang 2004). Recent work has shown that standard sensor nodes, such as the MICA2 motes, can be compromised in less than one minute (Hartung 2004). While these results are not surprising given that the MICA2 lacks tamper resistant hardware protection, they provide a cautionary note about the speed of a well-trained attacker. If an adversary compromises a sensor node, then the code inside the physical node may be modified.

Countermeasures

Now we are in a position to describe the measures for satisfying security requirements and protecting the sensor network from attacks. We start with key establishment in wireless sensor networks, which lays the foundation for the security in a wireless sensor network, followed by defending against DoS attacks, secure broadcasting and multicasting, defending against attacks on routing protocols, combating traffic analysis attacks, defending against attacks on sensor privacy, intrusion detection, secure data aggregation, defending against physical attacks, and trust management.

Key Management Fundamentals

Key management issues in wireless networks are not unique to wireless sensor networks. Indeed, key establishment and management issues have been studied in depth outside of the wireless networking arena. Traditionally, key establishment is done using one of many public-key protocols. One of the more common is the Diffie-Hellman public key protocol, but there are many others. Most of the traditional techniques, however, are unsuitable in low power devices such as wireless sensor networks. This is due largely to the fact that typical key exchange techniques use asymmetric cryptography, also called public key cryptography. In this case, it is necessary to maintain two mathematically related keys, one of which is made public while the other is kept private. This allows data to be encrypted with the public key and decrypted only with the private key. The problem with asymmetric cryptography, in a wireless sensor network, is that it is typically too computationally intensive for the individual nodes in a sensor network. This is true in the general case, however, Gaubatz (2004), Gura (2004), Malan (2004), and Watro (2004) show that it is feasible with the right selection of algorithms.

Symmetric cryptography is therefore the typical choice for applications that cannot afford the computational complexity of asymmetric cryptography. Symmetric schemes utilize a single shared key known only between the two communicating hosts. This shared key is used for both encrypting and decrypting data. The traditional example of symmetric cryptography is data encryption standard (DES). The use of DES, however, is quite limited due to the fact that it can be broken relatively easily. In light of the shortcomings of DES, other symmetric cryptography systems have been proposed including triple DES (3DES), RC5, AES, and so on.

One major shortcoming of symmetric cryptography is the key exchange problem. Simply put, the key exchange problem derives from the fact that two communicating hosts must somehow know the shared key before they can communicate securely. So the problem that arises is how to ensure that the shared key is indeed shared between the two hosts who wish to communicate and no other rogue hosts who may wish to eavesdrop. How to distribute a shared key securely to communicating hosts is a nontrivial problem since predistributing the keys is not always feasible.

Key Establishment

One security aspect that receives a great deal of attention in wireless sensor networks is the area

of key management. Wireless sensor networks are unique (among other embedded wireless networks) in this aspect due to their size, mobility, and computational/power constraints. Indeed, researchers envision wireless sensor networks to be orders of magnitude larger than their traditional embedded counterparts. This, coupled with the operational constraints described previously, makes secure key management an absolute necessity in most wireless sensor network designs. Because encryption and key management/establishment are so crucial to the defense of a wireless sensor network, with nearly all aspects of wireless sensor network defenses relying on solid encryption, we first begin with an overview of the unique key and encryption issues surrounding wireless sensor networks before discussing more specific sensor network defenses.

WSN Key Management Protocols

Random key predistribution schemes have several variants. Eschenauer and Gligor (2002) propose a key predistribution scheme that relies on probabilistic key sharing among nodes within the sensor network. Their system works by distributing a key ring to each participating node in the sensor network before deployment. Each key ring should consist of a number randomly chosen keys from a much larger pool of keys generated offline. An enhancement to this technique utilizing multiple keys is described by Chan (2003). Further enhancements are proposed by Deng (2005) and (Liu 2005) with additional analysis and enhancements provided by Hwang (2004). Using this technique, it is not necessary that each pair of nodes share a key. However, any two nodes that do share a key may use the shared key to establish a direct link to one another. Eschenauer and Gligor show that, while not perfect, it is probabilistically likely that large sensor networks will enjoy shared-key connectivity. Further, they demonstrate that such a technique can be extended to key revocation, rekeying, and the addition/deletion of nodes. The LEAP protocol described by Zhu et al. (2003) takes an approach that utilizes multiple keying mechanisms. Their observation is that no single security requirement accurately suites all types of communication in a wireless sensor network. Therefore, four different keys are used depending on whom the sensor node is communicating with. Sensors are preloaded with an initial key from which further keys can be established. As a security precaution, the initial key can be deleted after its use in order to ensure that a compromised sensor cannot add additional compromised nodes to the network.

In *PIKE* (Chan 2005), Chan and Perrig describe a mechanism for establishing a key between two sensor nodes that is based on the common trust of a third node somewhere within the sensor network. The nodes and their shared keys are spread over the network such that for any two nodes A and B, there is a node C that shares a key with both A and B. Therefore, the key establishment protocol between A and B can be securely routed through C.

Huang et al. (2003) propose a hybrid key establishment scheme that makes use of the difference in computational and energy constraints between a sensor node and the base station. They posit that an individual sensor node possesses far less computational power and energy than a base station.

In light of this, they propose placing the major cryptographic burden on the base station where the resources tend to be greater. On the sensor side, symmetric-key operations are used in place of their asymmetric alternatives. The sensor and the base station authenticate based on elliptic curve cryptography. Elliptic curve cryptography is often used in sensors due to the fact that relatively small key lengths are required to achieve a given level of security.

Huang et al. also use certificates to establish the legitimacy of a public key. The certificates are based on an elliptic curve implicit certificate scheme (Huang et al., 2003). Such certificates are useful to ensure both that the key belongs to a device and that the device is a legitimate member of the sensor network.

Each node obtains a certificate before joining the network using an out-of-band interface.

WSN and Public Key Cryptography

Two of the major techniques used to implement public-key cryptosystems are RSA and elliptic curve cryptography (ECC). Traditionally, these

have been thought to be far too heavy in weight for use in wireless sensor networks.

Recently, however, several groups have successfully implemented public-key cryptography (to varying degrees) in wireless sensor networks. Gura et al. (2004) report that both RSA and elliptic curve cryptography are possible using 8-bit CPUs with ECC, demonstrating a performance advantage over RSA. Another advantage is that ECC's 160 bit keys result in shorter messages during transmission compared the 1024 bit RSA keys. In particular Gura et al. demonstrate that the point multiplication operations in ECC are an order of magnitude faster than private-key operations within RSA, and are comparable (though somewhat slower) to the RSA public-key operation.

Watro et al. (2004) show that portions of the RSA cryptosystem can be successfully applied to actual wireless sensors, specifically the UC Berkeley MICA2 motes (Hill et al., 2000). In particular, they implemented the public operations on the sensors themselves while offloading the private operations to devices better suited for the larger computational tasks. In this case, a laptop that was the TinyPK system described by Watro (2004) is designed specifically to allow authentication and key agreement between resource constrained sensors. The agreed upon keys may then be used in conjunction with the existing cryptosystem, TinySec (Karlof 2003). To do this, they implement the Diffie-Hellman key exchange algorithm and perform the public-key operations on the Berkeley motes.

The Diffie-Hellman key exchange algorithm used by Malan et al. (2004) is detailed in the following. In this case, a point G is selected from an elliptic curve E, both of which are public. A random integer KA is selected, which will act as the private key. The public key (TA in the case of the sender) is then TA = KA * G. The receiver performs a similar set of operations to compute TB = KB * G. Both peers can now easily compute the shared-secret using their own private keys and the public keys that have been exchanged. In this case, the sender computes KA * TB = KA * KB * G while the receiver computes KB * TA = KB * KA * G. Because KA * TB = KB * TA, the sender and the receiver now share a secret key.

DoS Countermeasures

Since denial-of-service attacks are so common, effective defenses must be available to combat them. One strategy in defending against the classic jamming attack is to identify the jammed part of the sensor network and effectively route around the unavailable portion. Wood and Stankovic (2002) describe a two phase approach where the nodes along the perimeter of the jammed region report their status to their neighbors who then collaboratively define the jammed region and simply route around it. To handle jamming at the MAC layer, nodes might utilize a MAC admission control that is rate limiting. This would allow the network to ignore those requests designed to exhaust the power reserves of a node. This, however, is not fool-proof as the network must be able to handle any legitimately large traffic volumes.

Overcoming rogue sensors that intentionally misroute messages can be done at the cost of redundancy. In this case, a sending node can send the message along multiple paths in an effort to increase the likelihood that the message will ultimately arrive at its destination. This has the advantage of effectively dealing with nodes that may not be malicious, but rather may have simply failed as it does not rely on a single node to route its messages. To overcome the transport layer flooding denial-of-service attack, Aura, Nikander and Leiwo (2001) suggest using the client puzzles posed by Juels and Brainard in an effort to discern a node's commitment to making the connection by utilizing some of their own resources. Aura et al. advocate that a server should force a client to commit its own resources first. Further, they suggest that a server should always force a client to commit more resources up front than the server. This strategy would likely be effective as long as the client has computational resources comparable to those of the server.

Detecting Node Replication Attacks

Parno et al. (2005) describe two algorithms: randomized multicast and line-selected multicast. Randomized multicast is an evolution of a node broad-

casting strategy. In the simple node broadcasting strategy each sensor propagates an authenticated broadcast message throughout the entire sensor network. Any node that receives a conflicting or duplicated claim revokes the conflicting nodes. This strategy will work, but the communication cost is far too expensive. In order to reduce the communication cost, a deterministic multicast could be employed where nodes would share their locations with a set of witness nodes. In this case, witnesses are computed based on a node's ID. In the event that a node has been replicated on the network, two conflicting locations will be forwarded to the same witness who can then revoke the offending nodes. But since a witness is based on a node's ID, it can easily be computed by an attacker who can then compromise the witness nodes. Thus, securely utilizing a deterministic multicast strategy would require too many witnesses and the communication cost would be too high.

FUTURE TRENDS

Research on WSN security is still in infancy. Many key issues have not been sufficiently detailed or have even remained unexplored. In the near future, advanced security features may be built into the sensor nodes available in the market. While their prospects look shiny, these security functionalities have surprisingly received little attention from the research community. In the following, we describe the most interesting (in our sense) WSN-related research aspects.

1. **Building security policies for WSNs:** Due to their ad hoc topology, WSNs can not conform to traditional rigid security policies. WSN-oriented security policies should be flask enough to support the continuously modified network constituency and structure. The WSN architecture should therefore be flexible in their support of security policies, providing sufficient mechanisms for supporting the wide variety of real-world security policies. Appropriate formalisms to build, model, validate, verify, and test such architectures should be evolved.
2. **Developing scalable security mechanisms:** A common practice is to use exaggerated tools of information security, which decrease efficiency and system availability and introduce redundancy. Another effect of exaggeration of the security mechanisms is increasing the system complexity, which later influences implementation of a given project in practice, especially increasing expenses and decreasing efficiency. The solution of this inconsistency seems to be the introduction of scalable security model, which can change the security level depending on particular conditions of a given case. In this chapter a mechanism, which can modify the level of information security for each phase of a protocol, is presented. Parameters, which influence modification of the security level, are the risk of successful attack, probability of successful attack, and some measures of independence (leading to completeness) of security elements. The used security elements, which take care of the protection of information, are based mainly on PKI services and cryptographic modules.
3. **Securing hybrid broadband wireless sensor networks (HBWSNs):** High-speed WSNs begin to be widely used in different applications. Securing the corresponding flows encompasses the development of novel concepts that do not rely on thorough inspection of the transmitted packets but rather on the control of a set of relevant samples that are representative with respect to the total flow.
4. **Defining secure correlation functions: Two novels aspects are being investigated in the field of WSN security:** blind correlation and recursive signature. The first consists in correlating encrypted events without revealing their content in order to optimize the use of networking and processing resources. The second is applicable when, within a transmission chain, a set of nodes recursively sign the event. This is a particularly challenging problem in the WSN context because the intermediary nodes are resource-impoverished.

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KEY TERMS

Camouflage: Adversaries can insert their node or compromise the nodes to hide in the sensor network. After that these nodes can masquerade as a normal node to attract the packets, then misroute the packets.

Denial-of-Service Attack: An attack aiming at disrupting the acquisition of information within a geographical zone or preventing the communication of alert and signalling messages between sensor nodes.

Key Management: Process of generating, validating, exchanging, and renewing asymmetric and symmetric keys.

Rate Monitoring Attack: A rate monitoring attack simply makes use of the idea that nodes closest to the base station tend to forward more packets than those farther away from the base station.

Wireless Sensor Network (WSN): Dense collection of tiny sensor motes deployed in a region of interest to gather information about a specific phenomenon for later analysis. WSNs allow ef-

ficient, distributed, and collaborative control of various natural and human events.

Wormhole Attack: In a wormhole attack, an attacker receives packets at one point in the network, "tunnels" them to another point in the network, and then replays them into the network from that point.

Chapter XXXVI
Routing Security in Wireless Sensor Networks

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ABSTRACT

Since routing is a fundamental operation in all types of networks, ensuring routing security is a necessary requirement to guarantee the success of routing operation. Securing routing task gets more challenging as the target network lacks an infrastructure-based routing operation. This infrastructure-less nature that invites a multihop routing operation is one of the main features of wireless sensor networks that raises the importance of secure routing problem in these networks. Moreover, the risky environment, application criticality, and resources limitations and scarcity exhibited by wireless sensor networks make the task of secure routing much more challenging. All these factors motivate researchers to find novel solutions and approaches that would be different from the usual approaches adopted in other types of networks. The purpose of this chapter is to provide a comprehensive treatment of the routing security problem in wireless sensor networks. The discussion flow of the problem in this chapter begins with an overview on wireless sensor networks that focuses on routing aspects to indicate the special characteristics of wireless sensor networks from routing perspective. The chapter then introduces the problem of secure routing in wireless sensor networks and illustrates how crucial the problem is to different networking aspects. This is followed by a detailed analysis of routing threats and attacks that are more specific to routing operation in wireless sensor networks. A research-guiding approach is then presented to the reader that analyzes and criticizes different techniques and solution directions for the secure routing problem in wireless sensor network. This is supported by state-of-the-art and familiar examples from the literature. The chapter finally concludes with a summary and future research directions in this field.

INTRODUCTION

Wireless sensor networks (WSNs) are gaining popularity due to the fact that they provide feasible and economical solution to many of the most challenging problems in a wide variety of applications such as military applications, healthcare, traffic monitoring, pollution/weather monitoring, wildlife tracking, remote sensing, and so forth. This has fuelled extensive research to address the critical issues of providing security, intrusion detection/tolerance, high availability, and survivability of the sensor network.

The issue of secure routing in wireless and mobile computing is a major challenging design factor in different networking aspects. However, the problem gets more complicated when considering infrastructure-less networks that exhibit even more constraints and new types of attacks. In the continuously and rapidly evolving area of wireless communication, the field of wireless sensor networks comes into the picture as a very hot area of research in all its aspects. WSN is a multihop network that is actually one type of ad hoc networks. However, WSN draws the special attention of researchers due to the fact that it exhibits more constraints and critical conditions than normal ad hoc networks in terms of power sources, computing capabilities, memory capacity, and other factors. This requires different approaches and protocol engineering directions from those applied to normal ad hoc networks.

WSNs are susceptible to several types of attacks at different layers of the network since they are normally deployed in open and unprotected environments and are constituted of cheap small devices with limited computational power, limited memory, and limited battery life. Nodes of a sensor network cannot be trusted for the correct execution of the critical network functions. Node misbehavior may range from simple selfishness or lack of collaboration due to the need for power saving, to active attacks aiming at denial-of-service and subversion of traffic. A sensor network without sufficient protection from these attacks may not be deployable in many areas. Intrusion preventive mechanisms such as encryption and authentication can be applied to protect WSNs against some types of attacks. Key management is the cornerstone of security services such as encryption and authentication in wireless sensor network. Research seeking low-cost key management techniques that can survive node compromises in sensor networks has been a very active area, yielding several novel key predistribution schemes. However, there are some attacks for which there is no known prevention method, such as wormhole attack. Moreover, there are no guarantees that the preventive methods will be able to hold the intruders. Hence it is necessary to use some mechanisms of intrusion detection. Besides preventing the intruder from causing damages to the network, the intrusion detection system can acquire information related to the attack techniques, helping in the development of better prevention systems.

One special aspect in WSN is the provision of secure routing. As mentioned previously, the nature of WSN complicates the security requirements and adds difficulties in solving security problems. In fact, secure routing in WSN is actually still not captured well in the research field. One main reason is that the design of a routing protocol is biased towards solving the problem of power limitations and reducing communication overhead while keeping security concerns at a later phase to be integrated with the current routing solutions.

Among different approaches in solving the problem of secure routing in WSN, reputation system-based solution is one technique that has generated enough interest among WSN researching community. Reputation systems attempt to provide security by allowing different nodes rate each other based on their routing activities and behavior analysis. When a node has an experience profile about its neighbors, it may select the node that it trusts more, and, hence, achieve a secure routing operation.

The rest of the chapter is organized as follows. Section 2 of the chapter provides the relevant background material covering an overview of WSN that includes WSN definition, sensor node structure, applications, and so forth. As WSN is a class of mobile ad hoc networks (MANET), the main differences between WSN and MANET will

be presented. These differences are explained in a way that emphasizes to the reader how they make WSN an independent research target as compared with MANET.

Section 3, being the routing security section, defines precisely the problem of secure routing in general. This section will discuss the requirements for secure routing in WSN. This will be followed by the challenges and constraints in WSN to achieve secure routing. After the reader understands the routing security problem in WSN, the reader will be given a critical discussion about the importance of this problem. This will also include an explanation of the relationship between routing security and different network aspects like survivability, connectivity and network partitioning, throughput, packet delay, and so forth.

Section 4 on routing attacks and threats presents in brief the different possible communication models and trust relationships between WSN nodes that a threat will be based on. It will clearly show how researcher assumptions on nodes communication models and nodes relationships will impact the security analysis. In this section, the reader will be provided with a global picture of the approaches and techniques that are used by the attackers. This will also include a discussion of the holes and weakness points that are exploited to achieve such attacks. Some examples of famous attacks will be given with explanation. The explanation will focus on how the attack works by exploiting the routing protocol aspects. Thus, the section will also show the robustness level that is provided by different routing protocols. How we can think secure and provide robust solutions against routing attacks and threats will be the subject of this section. The section gives examples of how an attack can be prevented or detected as a tip for a more general approach.

Section 5, "Routing Security Solutions and Techniques," explains the objectives to be met when developing a routing security solution. These security objectives are explained under the lights of WSN constraints. Thus, the reader will be aware of the tradeoffs that should be considered in the design. A first step in the solution design is to decide whether the solution will prevent the attack or avoid it after detection. This section gives a comparison between these approaches based on the severity of the threats and WSN conditions and resources availability. In this section, cryptographic-based and noncryptographic-based approaches will be discussed and the tradeoffs with resources will also be analyzed. Examples of such solutions will be provided with a focus on how these solutions meet secure routing goals and what drawbacks they exhibit. Reputation-based solution will be discussed as a detection approach by presenting the general concept of reputation systems, followed by suggestions and approaches in reputation system solutions that can fit WSN secure routing requirements.

BACKGROUND

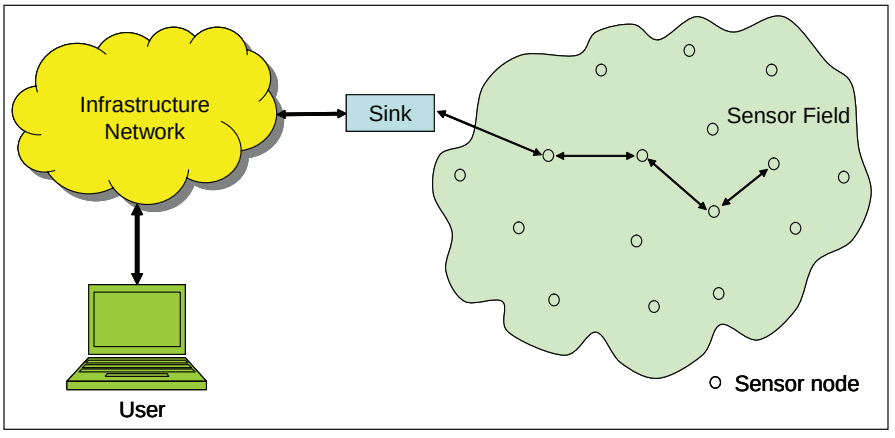
Wireless Sensor Network Overview

WSN is an ad hoc-like deployment of a large number of sensor nodes that are intended to monitor and communicate information pertaining to a phenomenon or an event of interest. The deployment is either random or utilizes predetermined locations near or inside the phenomenon. The typical deployment scenario of WSN is depicted in Figure 1, where a number of sensor nodes are scattered in the sensor field. The sensor nodes collect data from the field and route the data through the multihop structure of the network to a specialized node referred to as the sink or base station. Finally, the sink may communicate the raw data or a processed version to the end-user utilizing an infrastructure network such as the Internet.

Applications of WSN

Due to the versatility and flexibility of WSN, it has found many applications especially in situations where direct probing or measurement of the event of interest is either costly or risky. WSNs facilitate many applications including:

Figure 1. Sensor nodes deployment in a sensor field



- **Military applications:**
  - Monitoring friendly forces, equipment, and ammunition
  - Battlefield surveillance
  - Reconnaissance of opposing forces and terrain
  - Targeting guidance
  - Battle damage assessment
  - Nuclear, biological ,and chemical (NBC) attack detection and reconnaissance
- **Environmental and precision agriculture Applications:**
  - Tracking the movements of birds, small animals, and insects
  - Monitoring environmental conditions that affect irrigation
  - Earth, and environmental monitoring in marine, soil, and atmospheric contexts
  - Forest fire detection
  - Meteorological or geophysical research
  - Flood detection
  - Pollution study
  - Fertilizer and humidity sensing for farms
- **Health applications:**
  - Providing interfaces for the disabled
  - Integrated patient monitoring
  - Administration in hospitals
  - Telemonitoring of human physiological data
  - Tracking and monitoring doctors and patients inside a hospital
- **Facility management and commercial aApplications:**
  - Managing inventory
  - Monitoring product quality
  - Robot control and guidance in automatic manufacturing environments
  - Interactive museums
  - Smart structures with sensor nodes embedded inside
  - Vehicle tracking and detection
  - Machine surveillance and preventive maintenance
  - Intelligent building
- **Telematics:**
  - For roads and traffic management

Sensor Node Structure

The basic structure of the sensor node is shown in Figure 2(a), while the protocol stack for the node is shown in Figure 2(b). The node contains an embedded system that performs the following main functions:

- **Sensing:** Every node should have the ability to observe and/or control the physical environment.
- **Computing:** The collected data from physical environment through sensing function are

processed to produce beneficial information.

- **Communication:** Every node should be able to communicate and exchange raw data or processed information among them.

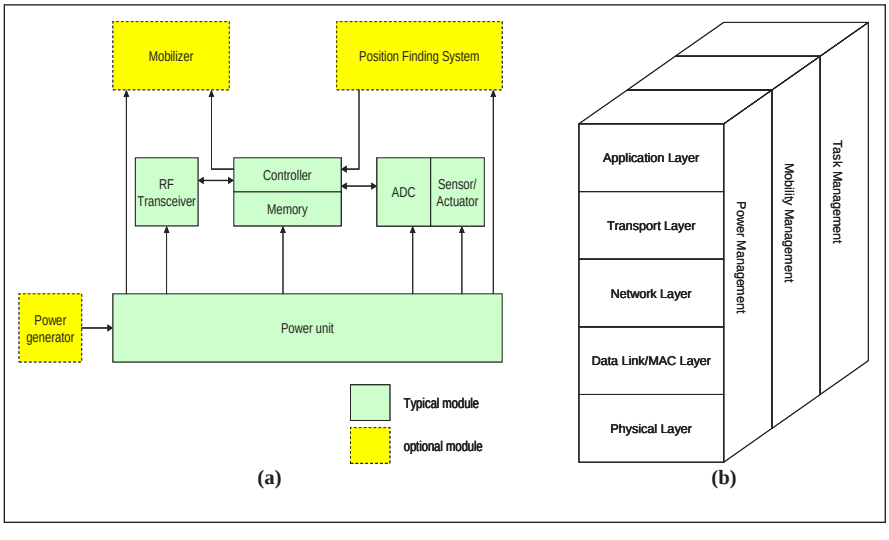
To accomplish the above tasks, the sensor node comprises of four main components: the controller/memory module, the power supply module, the RF transceiver module, and the sensors/actuators module. In addition, the sensor unit may optionally contain two other modules, namely, the position finding module and the mobilizer module. While the former module is sometimes needed to determine the location of the node, the latter allows mobilizing the node to carry out certain tasks in the field of interest. The brief description of these modules of a sensor node is presented next.

Controller/memory module: The controller consists of a processor and a memory system. The processor manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks. The memory system stores data, software, and application programs required to run the node. Though the higher computational powers are being made available in smaller and smaller processors and controllers, processing and memory units of sensor nodes are still scarce resources. For instance, the processing unit of a smart dust mote prototype is a 4 MHz Atmel AVR8535 micro-controller with 8 KB instruction flash memory, 512 bytes RAM, and 512 bytes EEPROM (Perrig, Szewezyk, Wen, Culler, & Tygar, 2001). TinyOS operating system is used on this processor, which has 3500 bytes OS code space and 4500 bytes available code space.

Power supply module: One of the most important components of a sensor node is the power unit. Since the sensor nodes are often inaccessible, power is considered a scarce resource and the lifetime of a sensor network depends on the lifetime of the power resources of the nodes. Power is also a scarce resource due to the size limitations. For instance, the total stored energy in a smart dust mote is of the order of 1 J (Pottie & Kaiser, 2000). It is possible to extend the lifetime of the sensor networks by energy scavenging, which means extracting energy from the environment. Solar cells are an example for the techniques used for energy scavenging.

Radio transceiver module: The radio transceiver unit is responsible for connecting the node to the network.

Figure 2. Wireless sensor network: (a) node structure, and (b) protocol stack



Sensors/actuators module: Sensing and actuator units are usually composed of sensors, actuators, and analog to digital (for sensing) and digital to analog (for actuating) converters (ADC/DAC). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC, and then fed into the processing unit or the controller. On the other hand, the digital signals produced by the controller are converted to analog signals by the DAC to feed the actuators.

Position finding module: In some instances, the operation of the sensor node, as in some of the routing techniques, requires knowledge of location with high accuracy. These nodes will be equipped with a module that is used to determine either the relative or absolute location of the node. The determination of the absolute location can be obtained using global positioning system (GPS), while the relative location can be calculated using the less expensive signal triangulation or multilateration techniques (Savvides, Han, & Srivastava, 2001).

Mobilizer module: For particular application of WSN, it may be required to move a subset of the deployed sensor node into specific positions in the field of interest. For these nodes, the mobilizer module allows the node to move or change its location to perform the required task.

WSN vs. MANET

While WSN and mobile ad hoc networks share a lot of commonalities, there are distinct differences that exist between the two technologies. These differences include the following characteristics.

Node population: Typically the number of nodes deployed in a WSN is orders of magnitude greater than the number of nodes in a MANET. This is of course a function of the application and the sensor field. In addition, wireless sensor nodes usually have shorter communication range compared to their counterparts in MANET. This implies that the deployment density for sensor nodes may be significantly higher than that for the MANET.

Resource constraints: An obvious difference between MANET and WSN is resource constraints. Resources include power, memory, and processing capabilities. Although both networks suffer from resource deficiency, WSNs are more constrained and limited by such resources, especially in power. MANET nodes are typically laptops or handheld devices that have greater provisions in terms of power and processing capability which is not the case for little sized sensor nodes. Any protocol design and implementation targeting WSN from the physical to the application layer must consider resource usage optimization not as an additional feature in the system but as a main design goal.

Communication and topology models: The most used communication model adopted for MANET is the point-to-point model. While this model is also applicable in WSN, other communication models such as broadcasting and multicasting are more realistic and representative of the intended applications. In addition, the topology for WSN is highly variable compared to that for MANETs. The loss of a sensor node due to a battery running out or destruction results in a topological change in the network for which the WSN has to respond and self-organize.

Application characteristics: WSN targets a great range of applications as mentioned in section 2.2. Therefore, WSN is expected to have different requirements in terms of node density, sensing functions, routing activity, and so forth compared to those for MANET. This variation also exists in MANET but to a lesser degree as the number of applications for ad hoc networks is not as great as that for WSN.

Addressing and identification: WSN nodes usually do not possess a unique identification ID as opposed to ad hoc node in a MANET where every node is identified by its media access control (MAC) address or the Internet address. Nodes within a sensor field organize and establish a mechanism to identify adjacent nodes and perform the required functionality.

ROUTING SECURITY

What is Routing Security

Routing is a fundamental operation in almost all types of networks because of the introduction of interdomain communication. Ensuring routing security is a necessary requirement to guarantee the success of routing operation. When we talk about secure routing, we are concerned with security problems that may occur due to improper actions from an assumed router. These undesired actions can be related either to the router identity or the router behavior. If the router has an undesirable identity or authorization, the router is considered as an intruder who might perform serious attacks. Such attacks can be avoided by providing security services that validate the routers' identities. On the other hand, a router that misbehaves in the network by performing undesirable routing operations also contributes to the routing security problem. However, the attacks caused by misbehaving routers can be avoided by mechanisms that validate and evaluate the router behavior in the network.

Secure routing tasks get more challenging as the target network lacks an infrastructure-based routing operation. This infrastructure-less nature that invites a multihop routing operation is one of the main features of WSN networks that raise the importance of secure routing problem in these networks. Moreover, the risky environment, application criticality, and resources limitations and scarcity exhibited by WSN networks make the tasks of secure routing much more challenging.

Why Routing Security is Important in WSN

Secure routing in WSN is important for both securing obtained information as well as protecting the network performance from degradation. Most WSN applications carry and deliver very critical and secret information like in military and health applications. A WSN network infected by malicious nodes can alter or inject incorrect information, misroute packets, analyze data, or do not forward packets to their destination. Thus, having a secure routing protocol or framework can protect data exchange, secure information delivery, and maintain and protect the value of the communicated information.

Insecure routing can cause performance degradation as well. For example, nonforwarding attacks decrease the system throughput since packets will be retransmitted many times and they are not delivered. Denial-of-service attacks can increase the packet delay since some nodes acting as routers will be busy in responding to the attack and enforced to delay the processing of other packets. An infected WSN network can be partitioned into different parts that cannot communicate among each other due to nonforwarding attacks. This leads to the demand of increasing the number of sensors or changing the node deployment to return the network connectivity. This is very expensive; however, it can be avoided if a good secure routing solution is adopted.

Network resources are also affected by insecure routing. For example, denial-of-service attacks effect resource availability, whether we consider an offended node as a resource for routing or we consider the availability of data itself. Also, this attack forces offended nodes to consume unnecessary energy on packet reception and processing.

As we can see, the information value and the network performance are directly affected by the security level of the routing operation in WSN. A secure routing solution, thus, should provide information protection and performance maintenance. However, any proposed solution should account for the overhead impact on the network performance. For example, a secure routing solution may introduce an overhead that decreases the network throughput. If this degradation is more than the one resulted from the attack; it is better not to implement the solution in this regard.

ROUTING ATTACKS AND THREATS IN WSN

The designing of a secure routing protocol becomes very essential as the weaker defender (i.e., sensor nodes) in the sensor network has the greatest inher-

ent disadvantage of insecure wireless communication, limited node capabilities, possible insider threats, and the stronger attacker has the all-time advantage of possessing powerful laptops with high energy and long range communication to launch severe attack to the network. Most of the routing protocols have not been designed with security as a goal. All of the proposed network routing protocols in the literature are more prone to attacks. Attackers can attract or repel traffic flows, increase latency, or disable the entire network, sometimes with little effort.

Threat Models

In order to define a robust security model, specification of both the security requirements and the threat model are required. The security requirements identify the properties that have to be enforced and the initial assumptions. The threat model formulates the hypothesis regarding the attacker's capabilities and its possible behavior. A common assumption is that the attacker is compliant with the Dolev-Yao threat model (Dolev & Yao, 1983) which is often used to formally analyze crypto-protocols in communication networks. According to this model, when two communicating parties communicate over an insecure channel, the attacker can gain control over the communication network to perform the following actions:

- Over hear the messages between the parties, intercept them, and prevent their delivery to the intended recipient.
- Introduce forged messages into the system using all the available information.

But this threat model also assumes that the end nodes are not themselves subject to attack. In order to take into account the distinguishing feature of WSNs that the sensors may be unattended and end nodes cannot, in general, be trusted, the following more powerful action is required to be included in the model:

- An attacker can capture a sensor node and acquire all the information stored within it.

Considering the above modified model, the attacks can be categorized as passive and active attacks. In passive attacks, eavesdropper can continuously monitor the whole sensor network and can launch two types of passive attacks: (i) cipher text attack wherein given the cipher text, the adversary tries to recover the encryption key, and (ii) chosen plain text attack wherein the attacker can feed the sensor with known data and then observe the encrypted message sent by the sensor. In active attacks, the attacker can capture a sensor, stealing all the information and keys stored in the sensor. Hence, providing, maintaining, and ensuring proper confidentiality and authenticity of data is a paramount importance within the limited inherent constraints of the underlying wireless sensor networks.

Sensor network attackers can be classified into two categories depending upon their capabilities (Karlof & Wagner, 2003). They are mote-class attacker and laptop-class attacker.

Mote-class attacker has access to a few ordinary sensor nodes with lesser capability and might only be able to jam the radio link in its immediate vicinity. They have limited range and cannot eavesdrop on entire network, moreover, cannot coordinate their efforts to bring down the network.

Laptop-class attacker has access to more powerful devices like laptops with greater battery power, more capable processor, a high-power transmitter, and a sensitive antenna. These attackers might be able to jam the entire network using a stronger transmitter and might be able to eavesdrop on an entire network. Laptop-class attackers might possess a high bandwidth, low-latency communication channel invisible to legitimate sensor nodes thereby setting up separate channels to allow such attackers to communicate and coordinate their efforts.

Further, sensor network attacks can be classified as outsider (external) attacks and insider (internal) attacks. Outsider attacks are launched by outsiders who have no special or legitimate access to the sensor network, that is, they do not have authentic keying material to participate in network operations as legitimate nodes. Insider attacks occur when an authorized participant in the sensor network has gone bad or compromised. The insider attack

may be mounted from either compromised sensor nodes running a malicious code or attackers using laptop-class devices to attack the network after stealing the key material, code and data from legitimate nodes. Outsider attackers, once in full control of certain nodes, can become insider ones able to launch more subtle attacks. Insider attacks are generally more difficult to defend against than the outsider ones because of their possession of keying material.

In most of the threat models proposed in the literature, it is assumed that the environments in which the sensors deployed are risky and untrusted. Each sensor trusts itself, but sensors do not trust each other. Further, it is assumed that all the compromised sensors in the sensor network are compromised by the same attacker and thus collude to compromise the network. The attacker may compromise multiple sensor nodes in the network, and there is no upper bound on the number of compromised nodes. However, the attacker cannot compromise the base station, also termed as sink, which is typically resourceful and well protected. Once a sensor node is compromised, all the secret keys, data, and code stored on it are exposed to the attacker. The attacker can load a compromised node with secret keys obtained from other nodes, termed as collision, among compromised nodes. In other words, the goal of the attacker is to uncover the keys used in the system in order to disrupt the network operation. In order to achieve this, the attacker compromises individual nodes and fosters collusion among nodes. The main objective of node collusion is to incrementally aggregate the uncovered keys of individual nodes to a level that all encrypted traffic in the network is completely revealed. It is also assumed that the attacker cannot successfully compromise a node during the sensor deployment phase which is short, that is, the interval of tens of seconds when each sensor bootstraps itself, during which the sensor nodes obtain their location information and derive few keys. Indeed, such attacks can be prevented in many of the real-life scenarios when appropriate network planning and deployment are carried out to keep away attackers during the bootstrapping process. However, it should be noted that stronger threat (attacker) models need to be applied when we consider tactical military network deployment for war-field surveillance, whereas for noncritical commodity, sensor networks a less strong threat model may suffice.

A new threat model to communication confidentiality in WSNs termed as "smart attacker model" is introduced by Di Pietro, Mancini, and Mei (2006). All the random-key predeployment schemes (see section 5 for detailed discussion) proposed in the literature use an oblivious attacker model that at each step the attack sequence randomly chooses a sensor node to tamper without taking advantage of the information regarding the keys acquired during the previous attacks. Contrary to this, the smart attacker model greedily uses the previous attacks keys acquired information to choose the best sensor to tamper with in order to compromise the communication confidentiality. This reduces greatly the level of communication confidentiality provided by all the random key predeployment schemes

Routing Attacks and Examples

Any event that decreases or eliminates a network's capacity to perform its expected function is termed as a denial-of-service attack or commonly known as a DoS attack (Wood & Stankovic, 2002). Some of the major causes for DoS attacks are hardware failures, software bugs, resource exhaustion, malicious attacks, and environmental conditions. A significant challenge in securing large sensor networks is their inherent self-organizing, decentralized nature. Many of the network deployments are vulnerable to immensely more powerful attackers. Considering the layered network architecture of sensor networks depicted in Figure 2(b), the DoS vulnerabilities to the first four layers of the stack can be identified (Wood & Stankovic, 2002) as:

- **Physical layer attacks:** The most common attacks to the physical layer of a WSN are jamming and node physical tampering.
- **Data link layer attacks:** Collisions, unfairness, or exhaustion of resources are the attacks that can be launched against the data link layer of a sensor network.

- **Network layer attacks:** The possible routing layer attacks are routing information spoofing, alteration or replay, blackhole and selective forwarding attacks, sinkhole attacks, Sybil attacks, wormhole attacks, HELLO flood attacks, and acknowledgement spoofing.
- **Transport layer attacks:** The most common attacks to transport layer are flooding attacks and desynchronization attacks.

Since our main focus in this chapter is towards routing security, a detailed discussion on network layer or routing attacks will be presented next.

Sensor network routing attacks can be classified into the following categories (Karlof & Wagner, 2003):

- Routing information spoofing, alteration or replay
- Blackhole and selective forwarding attacks
- Sinkhole attacks
- Sybil attacks
- Wormhole attacks
- HELLO flood attacks
- Acknowledgement spoofing

Routing information spoofing, alteration, or replay: Targeting the routing information exchanged between the nodes is the most direct attack against a routing protocol. By spoofing, altering, or replaying routing information, an attacker can disrupt the network by creating routing loops, attracting or repelling network traffic, extending or shortening source routes, generating false error messages, partitioning the network, or increasing the end-to-end latency.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, geographic routing (e.g., GPSR, geographic and energy aware routing [GEAR]), minimum cost forwarding, rumor routing, energy conserving, and topology maintenance protocols (e.g., SPAN, GAF, CEC, AFECA) are prone to bogus routing information attacks.

For example, since routing updates are not authenticated in a TinyOS beaconing protocol, it is possible for any malicious node to claim itself to be a base station and become the destination of all traffic in the network. Mote class attackers can create very easily routing loops by spoofing routing updates. In GPSR, an adversary can forge location advertisements to create routing loops in data flows without having to actively participate in packet forwarding.

Black hole and selective forwarding attack: Multihop networks basically work on the assumption that nodes will participate faithfully in the forwarding of the received messages. In a blackhole attack, a malicious node refuses to forward every packet it receives thereby behaving like a block hole. In a selective forwarding attack, a malicious node selectively forwards the packets, that is, a malicious node may refuse to forward certain messages and simply drop them thereby ensuring that these packets are not propagated any further. The malicious node interested in suppressing or modifying the packets originating from a few selected nodes can reliably forward the remaining traffic thereby limiting the suspicion of its misbehavior. In order to launch a selective forwarding attack effectively, the attacker must follow the path of least resistance and attempt to include explicitly the attacker's self on the actual path of the data flow.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, geographic routing (e.g., GPSR, GEAR), minimum cost forwarding, clustering-based protocols (e.g., LEACH, TEEN, PEGASIS), and rumor routing, are highly prone to selective forwarding attacks.

For example, In LEACH protocol, nodes choose a cluster-head based on received signal strength. A laptop-class attacker can take advantage of this to send a powerful advertisement to all nodes in the network in order to mount a selective forwarding attack on the entire network using a small number of nodes if the target number of cluster-heads or the size of the network is sufficiently small.

Sinkhole attacks: In a sinkhole attack, the goal of the attacker is to attract nearly all the traffic from a particular region through a compromised node, thereby creating a metaphorical sinkhole with the attacker at the center. Sinkhole attacks typically work by making a compromised node appear especially attractive to surrounding nodes with respect to the routing algorithm.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, minimum cost forwarding, and rumor routing are prone to sinkhole attacks

For example, a laptop-class attacker with a powerful transmitter can actually provide a high quality route by transmitting with enough power to reach the base station in a single hop. Because of this high quality route through the compromised node, each neighboring node of the adversary will forward packets destined for a base station through the adversary and also propagate the attractiveness of the route to its neighbors. Due to the specialized communication pattern used, hierarchical sensor networks are highly susceptible to sinkhole attacks. In hierarchical sensor networks, all packets share the same ultimate destination, that is, a base station; a compromised node is required only to provide a single high quality route to the base station in order to attract a potentially large number of nodes.

Wormhole attacks: In the wormhole attack, an attacker tunnels messages received in one region of the network over a low-latency link and replays them in a different region. Wormhole attacks more commonly involve two distant malicious nodes colluding to understate their distance from each other by relaying packets along an out-of-bound channel available only to the attacker. An adversary situated close to a base station may be able to completely disrupt routing by creating a well-placed wormhole. An adversary could convince nodes who would normally be multiple hops from a base station that they are only one or two hops away via the wormhole. This can create a sinkhole since the adversary on the other side of the wormhole can artificially provide a high quality route to the base station thereby drawing through it potentially all traffic in the surrounding area if alternate routes are significantly less attractive. This will be the case always when the endpoint of the wormhole is relatively far from a base station. Wormholes are normally used in combination with selective forwarding. Detection becomes potentially difficult when used in conjunction with the Sybil attack.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, minimum cost forwarding, and rumor routing are prone to wormhole attacks

For example, protocols that construct a topology initiated by a base station are most susceptible to wormhole and sinkhole attacks. A wormhole is most effective when used to create sinkholes or artificial links that attract traffic. In sensor network employing TinyOS beaconing protocol, a powerful laptop-class attacker can launch a combined wormhole/sinkhole attack.

Sybil attacks: In a sybil attack, a single node presents multiple identities to other nodes in the network. An attacker can advertise multiple bogus nodes surrounding each target in a circle or sphere region, each claiming to have maximum energy.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, geographic routing (e.g., GPSR, GEAR), rumor routing, and energy conserving and topology maintenance protocols (e.g., SPAN, GAF, CEC, AFECA) are prone to Sybil attacks

For example, Sybil attacks pose a significant threat to geographic routing protocols. Location aware routing often requires nodes to exchange coordinate information with their neighbors to efficiently route geographically addressed packets. It is only reasonable to expect a node to accept but a single set of coordinates from each of its neighbors, but by using the Sybil attack an adversary can be in more than one location at once. GEAR tries to distribute the responsibility of routing based on remaining energy, so an appropriate attack would be to always advertise maximum energy as well.

HELLO flood attacks: In many routing protocols, nodes broadcast HELLO packets to announce their presence to their neighbors, and a node receiving such a packet may assume that it is within the normal radio range of the sender. This assumption can be exploited by a laptop-class attacker by broadcasting routing and other information with large enough transmission power in order to convince every node in the network that the adversary is its neighbor. The HELLO flood attack uses a single hop broadcast to transmit a message to a large number of receivers.

For example, an attacker advertising a very high-quality route to the base station to every node in the network can cause a large number of nodes to attempt to use this route, but those nodes sufficiently far away from the attacker will be sending their messages into oblivion thereby putting the network in a state of confusion. An attacker does not necessarily need to be able to construct legitimate traffic in order to use the HELLO flood attack. The attacker can simply rebroadcast overhead packets with enough power to be received by every node in the network. HELLLO floods can also be thought of as one-way, broadcast wormholes.

Most of the sensor network routing protocols such as TinyOS beaconing, directed diffusion and its multipath variant, minimum cost forwarding, clustering-based protocols (e.g., LEACH, TEEN, PEGASIS), and energy conserving and topology maintenance protocols (e.g., SPAN, GAF, CEC, AFECA) are prone to HELLO Flood attacks.

For example, in sensor network employing TinyOS beaconing protocol, a laptop-class attacker with a powerful transmitter can launch a HELLO flood attack to broadcast a routing update powerful enough to reach the entire network thereby causing every node to mark the attacker as its parent. Most nodes will be likely out of normal radio range of both a true base station and the attacker. The network is crippled as the majority of the nodes are stranded sending packets into oblivion.

In a sensor network employing minimum cost forwarding protocol, a laptop-class attacker can use the HELLO flood attack to disable the entire network by transmitting an advertisement with cost zero powerful enough to be received by every node in the network. In LEACH protocol, nodes choose a cluster-head based on received signal strength. A laptop-class attacker can take advantage of this to make every node choose the attacker as its cluster-head by using the HELLO flood attack to send a powerful advertisement to all nodes in order to disable the entire network.

Acknowledgement spoofing: Several sensor network routing algorithms that rely on implicit or explicit link layer acknowledgements are susceptible to acknowledgement spoofing. Due to the inherent broadcast medium, an attacker can spoof link layer acknowledgements for "overheard" packets addressed to the neighboring nodes with the main objective to convince the sender that a weak link is strong or that a dead or disabled node is alive.

For example, a routing protocol may select the next hop in a path using link reliability. A subtle way of manipulating such a scheme is to artificially reinforce a weak or dead link. Since packets sent along weak or dead links are lost, an adversary can effectively mount a selective forwarding attack using acknowledgement spoofing by encouraging the target node to transmit packets on those links.

Countermeasures Against Routing Attacks

Countermeasures against outsider attacks: The majority of outsider attacks against sensor network routing protocols can be prevented by simple link layer encryption and authentication using a globally shared key. Link layer acknowledgements can also be authenticated. In this case, Sybil attack is no longer relevant since nodes are unwilling to accept a single identity of the attacker. The majority of selective forwarding and sinkhole attacks are not possible because the attacker is prevented from joining the network. Although an attacker is prevented from joining the network, nothing prevents the attacker from using a wormhole to tunnel packets sent by legitimate nodes in one part of the network to legitimate nodes in another

part to convince them that they are neighbors or amplifying an overheard broadcast packet with sufficient power to be received by every node in the network.

Countermeasures against insider attacks: In the presence of insider attacks or compromised nodes, link layer security techniques using a globally shared key proves completely useless. Insiders can attack the network by spoofing or injecting bogus routing information, creating sinkholes, selectively forwarding packets, using Sybil attack, and broadcasting HELLO floods. More sophisticated defense mechanisms are needed to provide reasonable protection against wormholes and insider attacks.

We present some of the countermeasures suggested in the literature (Karlof & Wagner, 2003; Mun & Shin, 2005) for routing attacks discussed in section 4.2. Note that the full effectiveness of these suggested countermeasures are yet to be proven.

Selective forwarding: The countermeasure used against selective forwarding attacks is to introduce redundancy to the network in the form of multipath routing. In this case, "n" disjoint paths are required to protect completely against selective forwarding attacks involving at most "n" compromised nodes, which is very difficult to create. The use of multiple braided paths (i.e., paths having common nodes but no common links) may provide probabilistic protection against selective forwarding. Allowing nodes to dynamically choose a packet's next hop probabilistically from a set of possible candidates can further reduce the chances of an attacker gaining complete control of a data flow.

Sybil attack: An insider attacker can participate in the network by using the identities of the nodes the attacker has compromised. The countermeasure here is to verify the identities of the participating nodes. One solution is to have every node share a unique symmetric key with a trusted base station. Two nodes can then communicate with each other by establishing a shared key after verifying each other's identity to implement an authenticated and encrypted link between them.

Wormhole and sinkhole attacks: Wormhole and sinkhole attacks are the hardest attacks to defend against, especially when the two are used in combination. Wormholes are hard to detect because they use a private, out-of-band channel invisible to the underlying sensor network. Sinkholes are difficult to defend against in protocols that use advertised information such as remaining energy or an estimate of end-to-end reliability to construct a routing topology because this information is hard to verify. Geographic routing protocols, however, are resistant to these attacks because messages are routed towards the physical location of the base station. False links will be detected by the neighboring nodes that figure out that the physical distance of an advertised route exceeds the radio signal range of motes. Though geographic routing can be relatively secure against wormhole, sinkhole, and Sybil attacks, a major problem lies with the trustworthiness of the location information advertised from neighboring nodes. Probabilistic selection of a next hop from several acceptable destinations or multipath routing to multiple base stations can tackle this problem to some extent.

A technique for detecting wormhole attacks known as "packet leashes" is presented by Hu, Perrig, and Johnson (2003) for MANETs. A leash is any information that is added to a packet designed to restrict the packet's maximum allowed transmission distance. There are two types of leashes: geographical leash and temporal leash. A geographical leash ensures that the recipient of the packet is within a certain distance from the sender. A temporal leash ensures that the packet has an upper bound on its lifetime, which restricts the maximum travel distance. Either type of leash can prevent wormhole attack because it allows the receiver of a packet to detect if the packet has traveled further than the leash allows. But it requires extremely tight time synchronization and is thus infeasible for most sensor networks. The best solution is to carefully design routing protocols

which avoid routing race conditions and make these attacks less meaningful.

HELLO flood attacks: The simplest countermeasure against HELLO flood attacks is to verify the bidirectionality of a link before taking meaningful action based on a message received over that link. However, this countermeasure is less effective when an attacker has a highly sensitive receiver as well as a powerful transmitter. Such an attacker can effectively create a wormhole to every node within the range of its transmitter/receiver. One possible solution to this problem is for every node to authenticate each of its neighbors with an identity verification protocol using a trusted base station. In such a case, adversary is required to authenticate itself to every victim before it can mount an attack; an attacker claiming to be a neighbor of an unusually large number of the nodes will raise an alarm.

Acknowledgement spoofing: The most obvious solution to this problem would be authentication via encryption of all sent packets and also packet headers. Since base stations are trustworthy, attackers must not be able to spoof broadcast or flooded messages from any base station. This requires some level of asymmetry wherein no node should be able to spoof messages from a base station; at the same time every node should be able to verify them. Authenticated broadcast is also useful for localized node interactions.

The clustering algorithms used for WSNs rely on the honesty of all participating nodes, allowing a malicious node to generate false information to ensure its selection as cluster head thereby allowing an adversary to launch a sleep deprivation attack. To counteract this, Pirretti, Zhu, Narayanan, McDaniel, Kandemir, and Brooks (2005) proposes three separate defense mechanisms, the random vote scheme (randomizing the cluster head selection), the round robbin scheme (cluster head selection in a round robbin fashion), and the hash-based cluster head selection scheme (dynamic clustering) to form clusters and the selection of cluster heads.

When the network size is limited or topology is well-structured or controlled, global topology knowledge can be leveraged in security mechanisms. Drastic or suspicious changes to the topology might indicate a node compromise, and appropriate action can be taken.

Countermeasures such as link-layer encryption and authentication, multipath routing, identity verification, bidirectional link verification, and authenticated broadcast can protect sensor network routing protocols against outsiders, bogus routing information, Sybil attacks, HELLO floods, and acknowledgement spoofing and it is possible to augment existing protocols with these mechanisms. Sinkhole attacks and wormhole attacks pose significant challenges to secure routing protocol design, and it is unlikely that there exists effective countermeasures against these attacks that can be applied after the design of the protocol has completed. Hence, it is very crucial to design routing protocols by considering these attacks initially in the design so that with proper implementation of various security mechanisms, that is, robust countermeasures, these attacks can become ineffective.

ROUTING SECURITY SOLUTIONS AND TECHNIQUES

Security Goals

Security problems in WSN at the network layer can be related to router identity and router behavior. Theses two issues highlight two main tasks when we consider designing a secure routing solution.

- **Securing packet content:** This task is concerned with identity related security problems. The goal of this task is to assure that the packet is not accessed by unauthorized nodes as it travels from the source to the destination. This task can be achieved if we can provide the following services:
  - **Data confidentiality:** In this service, only the destination node should be able to access the packet content initiated

from the source node. Any intermediate router must not have any access to such information. As we can see here, the access of the packet is restricted to the destination node. Thus, if a node other than the destination accesses the packet, it means that the destination identity has been compromised.

    - **Data integrity:** When a destination node receives a message from a source, the destination should be able to detect any change that could occur in the massage.

- **Securing packet delivery:** This task deals mainly with behavior related security problems. Its objective is to guarantee that any packet transmitted will be ultimately received at the target destination. Thus, a misbehaving router node should not be able to drop a packet, misroute the packet, or deny the ability of routing of other nodes by denial-of-service attacks. This task can be interpreted in terms of a security service called data availability.
    - **Data availability:** If a node A is authorized to get information from another node B, node A should acquire this information at any time and without unreasonable delay.

There are many solutions and different approaches to achieve these tasks. However, the designer should be aware of the suitability of the solution with WSN tight constraints.

Some important guidelines that a designer should consider in the solution are:

- The solution should conserve energy as it is the rarest resource in WSN nodes. Energy conservation can be achieved by modifying an existing solution to reach the least possible energy consuming solution that can guarantee a certain level of security. Another possible approach is to make the design energy-aware in the sense that it adapts itself to the energy demands.
- The solution should not consume much memory or processing cycles. This is because security is considered as an added feature that must not compete with the application tasks in sharing memory or CPU usage. Thus, security overhead must be reasonable to keep WSN service throughput and general performance almost not affected.
- The solution proposed does not need to solve all security problems. However, a problem tackled by the proposed solution should be effective and robust. Such focused solutions should have the ability to be integrated with other solutions. This means that the design has to be flexible and has reasonable assumptions regarding the impact of nonsolved problems.
- The more modular the design is, the more robust the solution will be against future attacks. Moreover, modular design approach introduces some dynamicity that meets the very active and dynamic nature of WSN.
- Any proposed solution should be considered from an implementation point of view. If a solution cannot be implemented, it will be useless. Implementability considers issues like affordability, technology availability, application needs for such a solution, and so forth.

Intrusion Prevention and Detection Approaches

An intrusion can be defined as a set of actions that can lead to an unauthorized access or alteration of a certain system. Security is one of the key challenges to creating a robust and reliable network. Network security solutions can be generally grouped into two main categories: intrusion prevention-based techniques and intrusion detection-based techniques. Intrusion prevention-based techniques such as encryption and authentication are often the first line of defense against attacks. These intrusion prevention techniques can deter attackers from malicious behavior and reduce intrusions effectively, but cannot totally eliminate intrusions. The task of intrusion detection systems (IDS) is to

monitor computer networks and systems with the main objective of detecting possible intrusions in the network, alerting users after intrusion detection, and excluding the attacker, that is, reconfiguring the network. Thus, intrusion detection systems are considered to be serving as the second line of defense by detecting existing intruders and are important in constructing highly survivable networks and have been accepted as an indispensable part of today's computer security systems.

Intrusion prevention-based techniques: Authentication and encryption-based security schemes for sensor networks are adaptations of security algorithms developed for MANETs. These adaptations aim to decrease the computation and communication overhead of these methods which were originally designed for more capable and less resource-constrained MANET nodes. Section 5 of this chapter briefly discusses a variety of approaches proposed in the literature for key agreement and key distribution for sensor networks. Prevention-based security schemes are difficult to implement especially over large scale sensor networks as these techniques are vulnerable to wireless networking challenges. Shared broadcast medium, the possibility of passive listening, and resource-limited network elements decrease the effectiveness of prevention mechanisms. The multihop nature of a network also necessitates additional trust requirements among the nodes and increases the vulnerabilities. It is not flexible to implement a dynamic public key cryptography scheme and to provide key exchanges with trusted central authority. On the other hand, symmetric key cryptography can be used to authenticate neighbors. In any case, powerful encryption schemes will not be available because of the computational capacity of the nodes. Thus, security provided to sensor networks with prevention only techniques is not always sufficient, or practical, because of the scalability problems, the computation, communication, and storage overhead associated with these methods. Hence, intrusion detection techniques are required to be incorporated to build a robust and reliable secure system. Numerous prevention-based mechanisms for wireless sensor networks have been proposed, but there are only a few recently proposed detection-based mechanisms for senor networks.

Intrusion detection-based techniques: Detection-based techniques are divided into two major categories: signature detection (a.k.a. misuse detection) and anomaly detection. Signature detection techniques match the known attack profiles with the current changes, whereas anomaly detection uses established normal profiles and detects unusual deviations from this normal behavior.

Misuse-based detection systems work based on a database of known attack signatures and system vulnerabilities and raise alarms when an activity matching a signature in the database is identified. Several methods have been proposed in the literature to model attack signatures and to search for a match, such as expert system, pattern matching, colored Petri-nets, and state transition analysis. Kaplantzis (2004) presents a comparative study of three classification techniques (i.e., k-means nearest neighbor classifiers, artificial neural networks, and support vector machines) in order to find the best performing classifiers in terms of speed and accuracy for an intrusion detection system using pattern matching. Classifiers are tools that partition sets of data into different classifications on the basis of specified features in that data. They showed that the support vector machines train in the shortest amount of time with an acceptable accuracy, while neural networks exhibit high accuracy at the cost of long training times. The benefits of misuse-based detection techniques are simplicity of these systems, the ability to detect attacks immediately after installation and that the signatures are based on well known intrusion activities and hence the detections are usually very accurate. In contrast, the major drawback of misuse-based detection system is the ability to manage effectively the signature database containing a huge amount of known attack patterns and updating the attack signatures as new attacks are published. These systems cannot detect unpublished attacks and are prone to circumventing false negative alarms and also the cost of generating signatures for all known attacks is very high.

Anomaly-based detection systems work based on the assumption that an intrusion can be detected by observing a deviation from normal or expected behavior of the system. These techniques buildup normal profiles from previously observed subject behavior and signal intrusions when the observed activities differ significantly from the normal behavior of the system. The major benefit of the anomaly-based detection technique is that it is very effective in defending against new attacks as it does not distinguish between known attacks and unknown attacks. However, such techniques are complex as they require a periodic online learning process in order to buildup up-to-date normal profiles and resource hungry as they are constantly generating logs and checking audit files. Moreover, anomaly-based intrusion detection systems tend to have high false alarm rates because the comprehensive knowledge of expected normal behavior of a system is hard to model. Hence, a major challenge in building anomaly-based IDS is to control effectively the false alarms. Another key challenge in identifying misbehaviors in wireless sensor networks is to develop techniques for detecting anomalies in the network, such that these techniques minimize their communication overhead and energy consumption in the network. Misbehaviors can be identified by analyzing sensor or traffic measurements to discriminate normal behavior from anomalous behavior. Anomaly detection in data with an unknown distribution is an important problem to be addressed in wireless sensor networks.

Several techniques have been proposed in the literature to identify anomalies and perform distributed data clustering in the context of MANETs. Clustering is the process of finding groups of similar data points, such that each group of data points is well separated (Han & Kamber, 2001). The Euclidean distance is used as the dissimilarity measure between pairs of data. A distributed k-means clustering algorithm has been proposed by Bandoyopadhya and Coyle (2006). An intrusion detection scheme has been proposed by Loo, Ng, Leckie, and Palaniswami (2006) to identify abnormal traffic patterns using fixed-width clustering. There has not been much work on the design of general intrusion detection system for wireless sensor networks, though the published works on intrusion detection in this area deal with specific kind of attacks or particular operations.

The work by Onat and Miri (2005) propose a predefined statistical model to identify anomalies in a distributed fashion wherein sensor nodes will have the ability to record simple statistics about the neighbors' behavior and detect anomalies in them. To make a sensor node capable of detecting an intruder, a simple dynamic statistical model of the neighboring nodes is built in conjunction with a low-complexity detection algorithm by monitoring received packet power levels and arrival rates. This work considers two types of attacks: node impersonation and resource depletion attack. These attacks reveal themselves by deviations from the normal transceiver and traffic behaviors.

A distributed, nonparametric anomaly detection scheme to identify anomalous measurements in sensor nodes has been proposed by Rajasegarar, Leckie, Palaniswami, and Bezdek (2006). In this approach, in order to minimize communication overhead, which is a major source of energy consumption, each individual sensor measurement is not sent to a central node for analysis. Instead the measurements are clustered and only cluster summaries are sent by the sensor nodes. Further, intermediate sensor nodes merge cluster summaries before communicating with other nodes. The clustering approach used here is based on the fixed-width clustering algorithm which produces a set of disjoint, fixed-width (or radius) clusters in the feature space. The anomaly detection algorithm used the average inter-cluster distance of the k-nearest neighbor (KNN) clusters to identify the anomalous clusters.

The work by Da Silva, Martins, Rocha, Loureiro, Ruiz, and Wong (2005) proposes a decentralized intrusion detection system for WSN which is based on the inference of the network behavior obtained from the analysis of events detected by a monitoring node. The only events considered are data messages listened to by the monitoring node that is not addressed to it and message collision when the monitoring node tries to send a message.

The approach proposed consists of three phases: data acquisition, rule application, and intrusion detection. In the data acquisition phase, messages are collected in a promiscuous mode and the important information is filtered before being stored for subsequent analysis. In the rule application phase the seven rules, interval rule, retransmission rule, integrity rule, delay rule, repetition rule, radio transmission rule, and Jamming rule are applied to the stored data and if the message fails the tests being applied, a failure is raised. In the intrusion detection phase, the number of raised failures is compared with the expected amount of occasional failures in the network and if the raised failures are found to be higher than the expected, then an intrusion detection is raised.

Agah, Das, and Basu (2004) introduce an intrusion detection scheme based on a noncooperative game approach. In every game theory problem, a payoff or utility function is required to be defined between players. A payoff function used in this work is based on two fundamental issues: cooperation and reputation. Payoff between two sensors is dependent on their distance and each node's transmitter signal strength. The more transmitter signal strength a node has, the more likely it cooperates with its close neighbors. In order to show how much each individual node is useful for the whole network, and gain better reputation among others, payoff between two sensor nodes should also represent how many packets each node receives and forwards at each time slot for the sake of others. Here, a nonzero sum, noncooperative game is defined between attacker and sensor nodes, where an attack is a denial-of–service attack, which is intended to be prevented. By using the game theory framework, authors show that the game achieves Nash equilibrium for both attacker and the network.

In the work proposed by Agah and Das (2007), the prevention of passive denial of service attack at routing layer in wireless sensor networks is formulated as a repeated game between an intrusion detector and nodes of a sensor network where some of these nodes act maliciously. The repeated games are associated with sequences of history-dependent game strategies. In order to prevent DoS attack, the interaction between a normal and a malicious node in forwarding incoming packets is captured as a noncooperative N player game. A framework is proposed to enforce cooperation among nodes and punishment for noncooperative behavior. The intrusion detector residing at the base station keeps track of node's collaboration by monitoring them. If performances are lower than some trigger thresholds, it means that some nodes act maliciously by deviation. The intrusion detection system rates all the nodes, which is known as subjective reputation (Michiardi & Molva, 2002), and the positive rating accumulates for each node as it gets rewarded.

An emotional ant-based approach to identify possible preattack activities in sensor networks is presented in the work IDEAS proposed by Bannerjee, Grosan, and Abraham (2005). Security monitoring in the sensor network is achieved by the foraging behavior of natural ant colonies. The work emphasizes the emotional aspects of agents where they can communicate the characteristics of a particular path among them through pheromone update. Therefore, in a sensor network if the emotional ants are placed, they could keep track of the changes in the network path, following a certain knowledge base of rules depicting the probable possibilities of attack. Once the particular path among the nodes is detected by the emotional ant, it can communicate the characteristics of the path through pheromone balancing to the other ants, and thereafter intrusion alarm can be raised.

Localization anomaly detection (LAD) proposed by Du, Fang, and Ning (2005) is a general scheme to detect localization anomalies that are caused by adversaries compromising the beacon nodes. Here localization anomaly problem is formulated as an anomaly intrusion detection problem, and a number of ways to detect localization anomalies are proposed. In the proposed work by Deng, Han, and Mishra (2004), a secure multipath routing to multiple destination base stations is designed to provide intrusion tolerance against isolation of a base station. Antitraffic analysis strategies are also proposed to help disguise the location of the base station from eavesdroppers.

Cryptography-Based Solutions

In order to achieve secure communication, robust cryptography schemes are required to ensure confidentiality (nondisclosure of secret information), integrity (prevention of data alteration), authentication (proof of identity), and nonrepudiation (unique, noncontestable message origin). To accomplish these goals, a combination of symmetric key algorithms (e.g., AES, DES, RC4), public key algorithms (e.g., RSA, ECC), and cryptographic hash functions (e.g., MD5, SHA) is commonly employed and RSA is by far the most widely used public key algorithm on the internet today. In general, they are three types of key establishment schemes: (1) trusted server based schemes, (2) self-enforcing schemes (3), and key predeployment or key predistribution schemes. Trusted-server-based schemes, for example, arbitrated keying protocol and Kerberos depend on a trusted server for key agreement among nodes. Because of the lack of trusted infrastructures, this type of scheme is not suitable for sensor networks. Self-enforcing schemes use the asymmetric encryption cryptography, such as the use of public key certificates which is limited by the current computation abilities and energy resources of sensor network technologies. Hence, key predistribution schemes are mainly considered for WSNs where the secret keys are distributed to all sensors before deployment on the ground.

An important challenge in the design of security for sensor networks is the problem of efficient key management. Efficient key management is still an important research area. Key management in WSNs involves the process of efficiently generating, storing, protecting, distributing, using, and destroying the cryptographic keys taking into account the prevailing conditions and constraints imposed by the sensor networks. The inherent characteristics of sensor nodes complicate the design of secure protocols for sensor networks and make the key management problem highly challenging. The limited computation, memory, and power resources of sensor nodes make it undesirable to use public-key cryptographic algorithms, such as Diffie-Hellman ley agreement or RSA signatures. Asymmetric cryptography may often require expensive computation which could expose power-constrained sensor nodes to denial-of-service (DoS) attacks. An attacker can perform battery-draining denial-of-service attacks by using digital signatures. In real-life challenging applications, networks of thousands of sensor nodes are deployed widely in public and hostile areas. Since these sensor nodes are low cost, and hence, not tamper-resistant, they are vulnerable to physical capture. An adversary may be able to undetectably take control of a sensor node and compromise the cryptographic keys. Since sensor nodes are usually deployed using random scattering, network protocols lack prior knowledge of which nodes will be within the communication range of each other after deployment. Due to the limited memory resources, the amount of memory required to establish unique keys with every one of the other nodes in the network is highly constrained. Due to the limited bandwidth and transmission power, the communication of large blocks of data becomes particularly too expensive.

WSN Key Management Schemes

Numerous key management schemes have been proposed for sensor networks. The objective of key management is to dynamically establish and maintain secure channels among communicating nodes. A key management framework for WSNs must deal with the following important issues:

- **Key peployment/key predistribution:** Deals with number of keys administrative keys (a.k.a. key encryption keys) required; the way the keys should be distributed before the nodes are deployed.
- **Key discovery:** Enables an arbitrary pair of sensors to discover the set of keys they share.
- **Key establishment/key setup:** Deals with establishing a secure session between a pair of nodes or a group of nodes
- **Node addition/rekeying:** Deals with how a node should be added to the network such that it is able to establish secure sessions with

existing nodes in the network in such a way that the backward secrecy is still preserved. Backward secrecy is maintained by means of periodically changing the traffic encryption keys. A newly added node can only obtain new traffic encryption key and not the previous encryption keys being used in the network and hence is not able to decipher previous traffic.

- **Node eviction/key revocation:** Deals with how a node should be evicted from the network such that it will not again be able to establish secure sessions with any one of the existing nodes in the network, and not be able to decipher future traffic in the network thereby preserving forward secrecy.

The metrics most commonly used in the published approaches to evaluate the performance of the key management schemes are local/global connectivity, resilience to sensor nodes capture, scalability, and memory efficiency. The distribution of keys to sensor nodes of large scale WSNs where physical topology is unknown prior to deployment would have to rely on key predistribution. Keys would have to be installed in sensor nodes before deployment in order to establish secure connectivity between nodes after deployment. Establishing secure pair-wise communications is a prerequisite for the implementation of secure routing and also useful for secure group communication.

Key management schemes in sensor networks can be classified broadly into dynamic or static key management schemes based on whether rekeying or updating of the administrative keys is enabled or not after network deployment. Static schemes assume a relatively static, short lived network where node replenishments are rare and keys outlive the network. Static key management schemes assume that once administrative keys are predeployed in the nodes, they will not be changed. Administrative keys are generated prior to deployment, assigned to nodes either randomly, or based on some deployment information. Another emerging class of schemes, termed dynamic key management schemes, assume long-lived networks with more frequent addition of new nodes, thus requiring network rekeying for sustained security and survivability after deployment. Dynamic key management schemes may change administrative keys periodically on demand or upon detection of node capture. The major advantage of dynamic keying is enhanced network survivability, since any captured key is replaced in a timely manner in a process known as rekeying. Another advantage of dynamic keying is providing better support for network expansion, upon adding new nodes, unlike static keying which use a fixed pool of keys and the probability of network capture does not necessarily increase.

Based on the key generation/distribution techniques used, these key management schemes can further be categorized into the following: pure probabilistic or random key predistribution schemes, polynomial-based key predistribution schemes, Blom's matrix-based key predistribution schemes, deterministic key predistribution schemes, and group key management schemes (combinatorial formulation) using exclusion-basis systems. Most of the existing schemes based upon the basic random key predistribution scheme introduced by Eschenauer and Gilgor (2002) are static key management schemes. Many of these schemes propose improvements over the basic scheme by using key polynomials, deployment knowledge (node locations, node clusters or group), as well as attack probabilities in certain portions of the network to enhance scalability and resilience to attacks.

The basic key predistribution scheme first proposed by Eschenauer and Gilgor (2002) is based on probabilistic key sharing among the nodes of a sensor network. This scheme uses a simple shared-key discovery protocol for key distribution, revocation, and node rekeying. In this scheme, before sensor nodes are deployed, an initialization phase, also known as key predistribution phase, is performed offline to generate a large random pool of P keys out of the total possible key space. For each node, k keys (also known as node's key ring) are randomly selected out of the large key pool P without replacement and loaded into each sensor node's memory. This key predistribution phase must ensure that only a small number of k

keys need to be stored in each sensor node's ring such that any two nodes will share at least one key with a chosen probability.

Q-composite random key predistribution scheme proposed by Chan, Perrig, and Song (2003) is a modification to the method proposed by Eschenauer and Gilgor (2002) where q common keys are required to match between neighboring nodes instead of a single common key, thereby making it more difficult to compromise communications. The motivating factor is that as the amount of required q common keys increases, it becomes exponentially harder for an attacker with a given set of keys to break a link.

Pseudo random key deployment scheme proposed by Di Pietro, Mancini, and Mei (2003) is a further improvement to the basic random predistribution scheme proposed by Eschenauer and Gilgor (2002), which allows more efficient key discovery procedure. In the key deployment phase, keys are assigned to a node according to the output of a pseudorandom generator with a publicly known seed and the node's ID as inputs. Di Pietro et al. (2006) further improve the above work by proposing a novel efficient and secure pseudo (ESP) random key deployment scheme that requires no message exchange between nodes to establish pair-wise keys, but only k applications of the pseudo-random function where k is the number of keys in the node's key ring, thereby minimizing energy consumption in the key discovery phase.

The work proposed by Du, Deng, Han, Chen, and Varshney (2004) presents a novel random key predistribution scheme that uses deployment knowledge. With such deployment knowledge, it is shown that each node only needs to carry a fraction of the keys required by the other random key predistribution schemes (Eschenauer & Gligor, 2002; Chan et al., 2003), while achieving improved level of connectivity (in terms of secure links), higher resilience against node capture, and reduction in amount of memory required.

The random key management scheme using both attack probabilities and deployment knowledge proposed by Chan, Poovendran, and Sun (2005) uses a subgrouping approach to isolate the effect of node captures into one specific subgroup, and to provide scalability for random key predistribution in clustered distributed sensor networks. This works considers the probability of node capture for each subgroup in order to design a scalable security mechanism that improves resilience to the attacks for the sensor subgroup with larger probability of node compromise. Hence this scheme can maintain flexibility in providing different security concerns for different sensor groups. Since sensor subgroups are located in different areas, they may have different chances of being attacked by the adversaries.

The work by Yang, Zhou, Zhang, and Wong (2006) proposes a polynomial-based key management scheme called group-to-group (G2G) pairwise key establishment which enables a node to communicate securely with nodes near a certain location using their location knowledge and the communicating nodes need not know each other's ID or need not be located within each other's communication range.

Zhang, Liu, Lou, and Fang (2006) propose a suite of location-based compromise-tolerant security mechanisms to mitigate the impact of compromised nodes. They propose the novel notion of location-based keys (LBKs) based on a new cryptographic concept called pairing which binds private keys of individual nodes to both their node IDs and geographic locations. The LBKs used in this approach can act as efficient countermeasures against a Sybil attack, identity replication attack, wormhole, and sinkhole attack. This work uses an identity-based cryptography (IBC) which is receiving extensive attention as a powerful alternative to traditional certificate-based cryptography (CBC). Its main idea is to make an entity's public key directly derivable from its publicly known identity information. Eliminating the need for public-key certificates and their distribution makes IBC much more appealing for securing WSNs, where the need to transmit and check certificates has been identified as a significant limitation.

The major challenge in dynamic keying is to design a secure yet efficient rekeying mechanism. A dynamic key management scheme is proposed by Jolly, Kuscu, Kokate, and Younis (2003) that is based on the identity-based symmetric keying.

In the work proposed by Eltoweissy, Heydaru, Morales, and Sadborough (2004), a combinatorial formulation of group key management problem is developed using exclusion-basis systems (EBS). A drawback of the basic EBS-based solution is that a small number of nodes may collude and collectively reveal all the network keys. In SHELL, Younis, Ghumman, and Eltoweissy (2006) propose a modification to EBS approach to address the collusion problem which performs location-based key assignments to minimize the number of keys revealed by capturing collocated nodes. LOCK proposed by Eltoweissy, Moharrum, and Mukkamala (2006) is an EBS-based dynamic key management scheme for clustered sensor network which uses key polynomials to improve the network resilience to collusion instead of location-based key assignment as in SHELL.

An important observation that can be drawn from these proposed schemes is that the location knowledge can be used to improve the performance of the key management schemes, such as the connectivity, resilience against nodes capture, and memory efficiency. Also it is evident that most of the key management solutions for wireless sensor networks are trying to find the better tradeoffs between system security (e.g., resilience to node capture) and network connectivity. All of them have weak and strong points. The diverse usages of wireless sensor networks make it unreasonable to try to find the single perfect scheme suitable for all situations.

Having provided a brief survey of the key management schemes to highlight the current developments in this key area, in the following section we briefly describe some protocols based on key predistribution schemes designed for WSN.

Protocols Based on Key Predistribution Schemes

Security protocols for sensor networks (SPINS): This work proposed in by Perrig et al. (2001) uses a hierarchical/centralized communication architecture that assumes a forest-like network formed around one or more base stations, which interfaces the sensor network to the outside network. SPINS has two security building blocks: secure network encryption protocol (SNEP) and the micro-version of the timed efficient streaming loss-tolerant authentication protocol (μTESLA). SNEP provides data confidentiality, two-party authentication, integrity, replay protection, and message freshness. μTESLA provides authentication for data broadcast. In the key deployment phase, every node shares a unique master key with the base station. In key establishment phase, two kinds of traffic (node to node communications and broadcasts by the base station) are secured. SNEP allows two nodes to establish a session key through the base station. μTESLA allows messages broadcast by the base station to be authenticated. When a new node is added, it is loaded with a unique master key that it shares with the base station. During a node eviction, the evicted node's master key is removed from the base station.

SNEP achieves semantic security with no additional transmission overhead by sharing a counter between the sender and receiver for the block cipher in counter mode. Since the counter value is incremented after each message, the same message is encrypted differently each time thereby preventing replay of old messages. To achieve two-party authentication and data integrity, a message authentication code (MAC) is used which enforces a message ordering and weak freshness. In μTESLA, the requirement of asymmetric mechanism for authenticated broadcast is achieved through a delayed disclosure of symmetric keys. μTESLA is based on one-way key chain. During initial set-up, the base station generates a one-way key chain of n keys by choosing the last key K_n randomly and generating the remaining values by successively applying a one way hash function F (such as MD5), that is, $K_i = F(K_{i+1})$. Every node synchronizes its time with the base station. Time is divided into uniform time intervals and the base station associates each key of the key chain with one time interval. To bootstrap μTESLA, the base station distributes the root of the key chain, K_n, to the sensor nodes. During the time interval i, the base station uses the key of the current time interval K_i to compute the MAC of the packets to

be broadcast in that interval and discloses the key $K_{i-\delta}$ that authenticates all the messages broadcast in and before the time interval i-δ. When a node receives the disclosed key $K_{i-\delta}$, it verifies the correctness of the key and then uses it to authenticate the message stored in its buffer received during the time interval i-δ.

Some remarks about this scheme are:

1. This scheme requires key server (base station) for the establishment of pair-wise keys compared to other schemes which only needs a bootstrap server (or base station) to initialize and deploy nodes.
2. SNEP protocol has low communication overhead, only 8 extra bytes per message.
3. SNEP is an end-to-end security protocol and cannot prevent routing misbehavior.
4. μTESLA provides a secure broadcast communication, which is a common and important communication pattern in almost all WSN applications.
5. μTESLA obtains routing security by authenticated routing that is achieved by deriving the operation on routing update packets and checking the correctness of the claiming parents by delayed key disclosure.
6. In μTESLA protocol, the base station and nodes are required to be loosely time synchronized.
7. The periodic key disclosure of μTESLA ensures compromising a single sensor does not reveal the keys of all the sensors in the network.

SeFER: secure, flexible and efficient routing protocol for distributed sensor networks: This work by Oniz, Tasci, Savas, Ercetin, and Levi (2005) presents a secure, flexible, and efficient routing protocol for sensor networks based on the basic random key predistribution scheme Eschenauer and Gilgor (2002) discussed in section 5.3.1. This protocol aims to establish secure paths in a sensor network between a controller and a set of nodes where each node has been assigned a set of randomly chosen keys out of a key pool. The primary aim of this protocol is to find routes from each sensor node to the controller with all routes from each sensor node to the controller secured. First, keys are predistributed to the sensor nodes and shared keys are discovered by the methods proposed in Eschenauer and Gilgor (2002). The protocol has six phases and it starts after each node discovers shared keys with its neighbors. The controller can communicate with the rest of the nodes indirectly via the level-one nodes, which are defined as the nodes in the wireless range of the controller. A route is formed using four phases: (1) level-one initialization phase (2), route learning phase (3), authenticate neighbor and shorter path discovery phase, and (4) key distribution phase. In the level-one initialization phase, the controller and nodes in the wireless range of the controller mutually authenticate themselves and the controller distributes the session key to be used in further phases. In the route learning phase, each node forwards messages containing route information to their downstream nodes and an initial set of routes is established. In the authentic neighbor and shorter path discovery phase, nodes broadcast messages in order to discover shorter paths to the controller. If shorter paths are found, these paths must be secured by assigning a key to that path which is performed by the controller in the key exchange phase. If the controller detects that a security breach has occurred during the execution of the routing protocol, it starts the session key expiration phase to invalidate the session key. If a legitimate sensor node is compromised, the controller starts the revocation phase in order to invalidate the key ring of the compromised node. Resilient to replay attacks is achieved in this protocol by associating each message with a nounce value proposed by Perrig et al. (2001) and a time stamp indicating expiration date.

Some remarks about this scheme are:

1. The proposed protocol is flexible such that it allows a tradeoff between route length and the route setup cost in terms of processing power and storage.
2. Different security needs for different location of nodes are not considered.

3. This scheme is less energy efficient because of the key discovery phase which requires a number of messages proportional to the number of keys assigned to each sensor.
4. The scalability of random key predistribution is a concern and not addressed.

Localized encryption and authentication protocol (LEAP): This work by Zhu, Setia, and Jajodia (2003) presents a complete key management framework for static WSNs which supports in-network processing, while at the same time restricts the security impact of a node compromise to the immediate network neighborhood of the compromised node. In order to meet the different security requirements of the messages exchanged between the sensor nodes, this protocol provides multiple keying mechanisms for securing node-to-base station traffic, base station to nodes traffic, local broadcasts, as well as node-to-node (pair-wise) communications. It also includes an efficient protocol for local broadcast authentication based on the use of one-way key chains. Each node shares four types of keys: an individual key, a group key, cluster keys, and pair-wise shared keys. In addition to these keys, a node also has to store a one-way key chain it creates, the commitments of the key chains its neighbors create, and the commitment of the base station's key chain.

Every node has a unique individual key that is only shared with the base station. This key is used for secure communication between the node and the base station. This key is generated and preloaded into each node prior to its deployment. A node uses its individual key to encrypt messages it sends to the base station. A group key is a global key shared by all the nodes in the network. This key is used by the base station for encrypting messages that are broadcast to the whole group. Messages broadcast by the base station are encrypted with the group key, but authenticated with μTESLA. A cluster key is a key shared by a node and all its neighbors and it is mainly used for securing locally broadcast messages such as routing control information or securing sensor messages which can benefit from passive participation. In passive participation, a node that overhears a neighboring sensor node transmitting the same reading as its own current reading can elect not to transmit the same, thereby saving energy consumption in sensor networks. A node's cluster key and one-way key chain allow its neighbors to authenticate its locally broadcast messages. The combination of cluster key and one-way key chain is interesting because the cluster key can be used to hide the keys in the key chain from cluster-outsiders, so that the keys do not need to be disclosed according to a schedule as in SPINS, and the keys in the key chain can be used for authentication as usual. Pair-wise shared key is a key each node shares with each of its immediate neighbors. Pair-wise keys are used for securing communications that require privacy or secure authentication. For example, a node can use its pair-wise keys to secure the distribution of cluster key to its neighbors, or to secure the transmission of its sensor readings to an aggregation node.

Some remarks about this scheme are:

1. This scheme is very effective in defending against many sophisticated attacks such as HELLO flood attack, Sybil attack and wormhole attack.
2. In this scheme, knowledge of node IDs is required to establish pair-wise keys among neighboring nodes.
3. It is assumed that all nodes are innocent within a short period after deployment.
4. This scheme is scalable and efficient in computation, communication, and storage.
5. Sensor deployment is considered to be static.
6. Different security needs for message exchanged between nodes for the hierarchical WSN are considered.
7. The issues regarding the impact of key sharing approach on in-network processing are addressed using cluster-keying mechanism.

Intrusion tolerant routing protocol for wireless sensor networks (INSENS): INSENS by Deng, Han, and Mishra (2002) constructs a tree-structured routing for wireless sensor networks. It aims to tolerate damage caused by an intruder

who has compromised deployed sensor nodes and is intent on injecting, modifying, or blocking packets. INSENS incorporates distributed lightweight security mechanisms, including one-way hash chains and nested keyed message authentication codes to defend against routing attacks such as wormhole attack. Adapting to WSN characteristics, the design of INSENS also pushes complexity away from resource-poor sensor nodes towards resource-rich base stations. It constructs forwarding tables at each node to facilitate communication between sensor nodes and a base station. The INSENS secure routing system is designed to prevent flooding attacks by allowing only base station to broadcast. The authentication of the base station is achieved via one-way hashes, so that individual nodes cannot spoof the base station and thereby flood the network. For unicast packets, nodes must first communicate through the base station, allowing the base station to act as a packet filter to prevent denial-of-service via a single node. To prevent advertisement of false routing data, control routing information is authenticated. A key consequence of this approach is that the base station always receives correct partial knowledge of the topology. Symmetric key cryptography is chosen for confidentiality and authentication between the base station and each resource-constrained sensor nodes, since it is considerably less compute-intensive than public key cryptography, and the base station is chosen as the central point for computation and dissemination of the routing tables. To address the notion of compromised nodes, redundant multipath routing is built into INSENS to achieve secure routing. The paths are designed to be disjoint, so that even if an intruder brings down a single node or path, secondary paths will exist to forward the packet to the correct destination.

Some remarks about this scheme are:

1. This scheme minimizes computation, communication, storage, and bandwidth requirements at the sensor nodes at the expense of increased computation, communication, storage, and bandwidth requirements at the base station.
2. Rather than rely on traditional intrusion-detection techniques, INSENS's strategy is to design a routing mechanism that is intrusion-tolerant.
3. An important property of INSENS is that while a malicious node may be able to compromise a small number of nodes in its vicinity, it cannot cause widespread damage in the network.

Non Cryptography-Based Solutions

Noncryptographic-based solutions are mainly concerned with behavior-related security attacks, such as nonforwarding, selective forwarding, and denial-of-service attacks. The basic concept in this general approach is to enable sensor nodes to be aware of their neighbors' behavior. When misbehavior is detected, the misbehaving node is avoided in routing.

The main features of such solutions as compared with crypto-based approach are:

- Crypto-based solutions are not robust against insider attacks in which the attacker is an identifiable and authorized member of the network. Such attacks can be done by compromised nodes or selfish nodes. Others are unintentionally done by faulty nodes (Josang & Ismail, 2002). However, security systems that depend on treating nodes' behavior instead of their identities are more robust. This is especially true in networks where such misbehavior is very possible or sometimes can be the dominant type of attacks, which is the case in WSN.
- Unlike node's identity, node' behavior is not fixed and can be dynamically changed in intelligent ways. Crypto-based solutions do not have the provision of this dynamic treatment. However, behavior-based approaches provide a means for an adaptive and dynamic decision making and reaction at the individual node level behavior.
- Cryptography overhead at the node level structure such as memory consumption and

computation complexities are all relieved in this approach. However, communication overhead and behavior knowledge exchange is more complicated here.

In literature, noncrypto approach is realized by the adoption of reputation systems. A reputation system is a type of cooperative filtering algorithm which attempts to determine ratings for a collection of entities that belong to the same community. Every entity rates other entities of interest based on a given collection of opinions that those entities hold about each other (Michiardi & Molva, 2002).

Reputation systems have recently received considerable attention in different fields such as distributed artificial intelligence, economics, evolutionary biology, and so forth. Most of the concepts in reputation systems depend on social networks analogy. As expected, reputation systems are complex in the sense that they do not have a single notion, but a single system will consist of multiple parts of notions. Thus, comparing reputation systems is, in fact, a very difficult problem. All known trials on such problem were based on qualitative approach. The work proposed by Mui, Halberstadt, and Mohtashemi (2002) makes an attempt on comparing reputation systems quantitatively based on game theory. The authors, thus, identify different notions of reputation systems like, contextualization, personalization, individual and group reputation, and direct and indirect reputation.

In the context of MANET and WSN (Buchegger & Boudec, 2003; Michiardi & Molva, 2002), the reputation of a node is the amount of trust the other nodes grant to it regarding its cooperation and participation in forwarding packets. Hence, each node keeps track of each other's reputation according to the behavior it observes, and the reputation information may be exchanged between nodes to help each other to infer the accurate values. There is a trade-off between efficiency in using available information and robustness against misinformation. If ratings made by others are considered, the reputation system can be vulnerable to false accusations or false praise. However, if only one's own experience is considered, the potential for learning from the experiences of others goes unused, which decreases efficiency.

Any reputation system in the context of MANET and WSN should, generally, exhibit three main functions (Djenouri et al., 2005):

- **Monitoring:** This function is responsible for observing the activities of the nodes of its interest set.
- **Rating:** A node will rate its interest set nodes based on the node's own observation (termed as first hand information), other nodes' observations that are exchanged among themselves (termed as second hand information), the history of the observed node, and certain threshold values.
- **Response:** Once a node builds knowledge about others' reputations, it should be able to decide upon different possible reactions it can take, like, avoiding bad nodes or even punishing them.

For secure routing problem in WSN, a reputation system can be a good solution for behavior-related problems. The efficiency of a proposed solution will depend on:

- The ability to monitor misbehavior events correctly.
- Using a good rating model that closely reflects the behavior of nodes.
- Developing good routing algorithms and decision criteria that try to select the most trusted routers and follow the least risky paths.

In literature, there are reputation-based solutions proposed for MANET such as CONFIDANT and CORE. The work, however, in WSN is not heavily studied. When considering WSN, reputation systems become more challenging for the first two phases, that is, monitoring and rating. Good monitoring requires a sensor node to be always awake overhearing others' packets which is an energy consuming operation. A possible approach is to make the responsibility of monitoring for a specific set of sensor nodes. However, this yields a poor rating mechanism. Moreover, the rating

model should be able to mathematically track the node behavior. Complex models may require a heavy processing task and memory usages. Theses resources are more in demand for data processing in the constrained WSN node.

In the following sections, we briefly describe some reputation-based solution designed for WSN.

Reputation-Based Solutions

SAR: Security-aware routing (SAR) proposed by Naldurg, Yi, and Kravets (2001) is a protocol derived from AODV and based on authentication and a metric called the hierarchal trust values metric. The hierarchal trust values metric governs routing protocol behavior. This metric is embedded into control packets to reflect the minimum trust value a router should have to be able to forward the received packet. This value is determined by the sender. A node that receives any packet can neither process it nor forward it unless it provides the required trust level present in the packet. Moreover, this metric is also used as a criterion to select routes when many routes satisfying the required trust value are available.

There are some problems and limitations in SAR:

- The routing operation needs to encounter a trusted route setup phase that is done using cryptographic authentication. This setup contributes some initial delay and requires some sophisticated crypto mechanisms.
- The trust metric used in SAR does not reflect exactly nodes' behavior; rather, they represent a "rank" that a node exhibits based on its identity and various security service provision. Thus, a trusted node in SAR is a node that has the appropriate rank that meets the routing requirements. To rank a node is another problem by itself that is not addressed very well.
- The routing decision rules in SAR are governed by the source, which makes the protocol less flexible.
- The routing decision is not to select the next hop but to decide to participate in the trusted route. As a result, selfish behavior is not addressed well in SAR.

TRANS: Proposed by Tanachaiwiwat, Dave, Bhindwale, and Helmy (2004), TRANS is a geographic routing protocol (GPSR-based) that provides security services using trust metric. It can be considered as a tight trust-based routing due to its specific targets and assumptions. It basically targets a misbehavior model in which an attacker selectively participates in routing signaling and control packets, but drops consistently queries and data packets. The protocol also assumes static sensor networks in which a tight mapping can be done between the nodes' identities and their locations. TRANS assumes a location-centric architecture that helps it in isolating misbehavior and establishing trust routing in sensor networks. As a result of that, the protocol assumes a certain communication model in which a single or multiple sinks initiate communication requests with various locations. During that phase, insecure locations are identified and blacklisted. The trust metric used to judge on location security is calculated based on nodes' experience among each other regarding their identities, link availability, and packet forwarding.

There are some problems and limitations in TRANS:

- In TRANS, the trust, in fact, is associated with locations rather than the nodes. The problem is that a location can be infected by a single node. The detour, then, will be around a larger area rather than a single node.
- Nodes located in proximity of an infected location might be also isolated. If not, they are also exposed to heavy routing duties that may induce selfish behavior.
- TRANS is limited by single or multiple sink communication models. This assumption is necessary for the efficient operation of the protocol.
- TRANS discusses approaches to decrease energy consumption due to the security

provision overhead. However, the protocol does not provide energy efficient techniques in the routing operation itself.

RGR: Resilient geographic routing (RGR) protocol proposed by AbuGhazaleh, Kang, and Liu (2005) is also a trust-based routing protocol that relies on a modified routing operation in GPSR. The basic idea in RGR is to assign an initial trust value for each node. Then, this value is incremented or decremented depending on the forwarding activity of the monitored node using a step function. The source node selects probabilistically a subset among its neighbors to forward its packet. This subset is selected from the node's forwarding set that exhibit trust values greater than a threshold.

There are some issues that are not considered in RGR.

- The protocol has no provision for energy efficiency.
- The protocol totally relies on trust-based forwarding. If a node is completely surrounded by misbehaving nodes, there is no other mechanism proposed to select a next hop since all nodes will be eliminated from the node's forwarding list.
- RGR is a multipath trust-based routing. Although multipath is important for reliable services, it is also believed that multipath routing is energy consuming, which is a very important issue to consider in WSN

Reputation-based framework for high integrity sensor networks: Ganeriwal and Srivastava (2004) propose a reputation-based framework for sensor networks where nodes maintain a reputation for other nodes and use it to evaluate their trustworthiness. The authors tried to focus on an abstract view that provides a scalable, diverse, and a generalized approach hoping to tackle all types of misbehaviors. They also designed a system within this framework and employed a Bayesian formulation, using a beta distribution model for reputation representation.

In this system, monitoring mechanism follows the classic watchdog methodology in which a node is assumed to be in a promiscuous mode to overhear neighbors' packets. Monitoring behavioral events can result in either cooperative event, α, in which a node is behaving well or noncooperative behavior, β, in which a node misbehaves. The count of each type is injected into the beta distribution formula as the distribution parameters to calculate the node reputation R. This formula calculates node's reputation based on first hand information. The reputation is updated as new monitoring events are obtained; second hand information is obtained and according to the age of the current reputation value. Any response action is based on selecting the most trusted node. The trust value of a node that is used for decision making is calculated as the statistical expectation of the reputation value.

This work, however; lacks some important points:

- The monitoring mechanism uses a normal watchdog mechanism that assumes a promiscuous mode operation for every node. This is not suitable for the WSN conditions in terms of energy scarcity as discussed earlier.
- The system does not show a practical solution implementation of monitoring and rating phases. From an implementation point of view, the study should provide an example of how monitoring and rating will be done under some application assumptions.
- The work does not propose a response methodology, for example, a routing algorithm. Instead, it leaves it an open issue. Therefore, the work lacks performance figures that can show the efficiency and security gain and benefits in routing operation that can be obtained in adopting this solution.

Reputation system-based solution for trust-aware routing: This work proposed by Maarouf and Naseer (2007) provides a reputation system-based solution for trust aware routing as a main security concern in WSN. In contrast to similar existing solutions for ad hoc networks like CORE (Michiardi & Molva, 2002) and CONFIDANT (Buchegger & Boudec, 2003) or those for WSN like RFSN (Josang & Ismail, 2002), this work proposes

solutions to focusing on satisfying WSN resources constraints and conditions, while maintaining the security requirements. Thus, the solution proposes new mechanisms and approaches that are customized for WSN constraints.

The work adopts a modular design approach by which it treats every individual component as a separate problem and studies it in the lights of WSN conditions adaptation and customization. The integrated reputation system is termed as senor node attached reputation evaluator (SNARE) (Maarouf & Naseer, 2006) which consists of three main components: monitoring component, rating component, and response component.

For the monitoring part, the work proposes a new monitoring strategy called efficient monitoring procedure in reputation system (EMPIRE) to solve the problem of efficient monitoring in WSN. Efficient monitoring should guarantee a satisfying level of capturing neighborhood activities, while trying to minimize power consumption, memory usage, processing activities, communication overhead, and so forth. In this work, monitoring efficiency is realized by the association between the nodal monitoring activity (NMA) and various performance measures. NMA is determined by the frequency of monitoring actions that a node takes to collect direct observation information. Reducing the frequency of monitoring, that is, reducing NMA, will affect the quantity and/or the quality of the obtained information. Thus, the performance measures will be affected. However, on the other hand, this reduction implies a saving in node's resources such as power, processing, and memory, which are the constraints that are faced in WSN. EMPIRE provides a probabilistic approach to reduce nodal monitoring activities, while keeping the performance of the system, from the behavior and trust awareness perspective, at a desirable level.

The rating component proposed in this work is called cautious rating for trust enabled routing (CRATER). Basically, this technique identifies three rating factors: first hand information (FHI), second hand information (SHI), and a defined period called neutral behavior period (NBP) during which a node is not doing any activity. The new contribution in CRATER is its mathematical approach that is used to rate nodes based on what is called cautious assumptions, which are very true in most WSN. These assumptions basically introduce the cases in which WSN nodes are very sensitive to hearing SHI and are concerned with their immediate neighbors.

Moreover, the rating component is evaluated by a novel and promising mechanism proposed to evaluate different reputation systems. The evaluation scheme is called reputation systems-independent scale for trust on routing (RESISTOR). RESISTOR is based on the analogy of the resistance phenomenon in electric circuits. It defines a metric called "resistance" to represent how much a node is resisting its malicious neighbors by finding the ratio between the risk value for the malicious node, which is computed by the monitoring node using CRATER, and the number of packets flowed into that malicious node. Then, based on that figure, which is called the resistance figure, the system performance is analyzed for evaluation.

Finally, the response component of the reputation system suggests a new routing protocol that aims to provide a secure packet delivery service guarantee by incorporating the behavior trust concept into the routing decision. The proposed geographic, energy and trust aware routing (GETAR) protocol is an enhanced version of the GEAR protocol (Yu, Govindan, and Estrin 2001). GEAR is basically a geographic routing protocol in which the next hop is selected based on two metrics: the distance between the next hop and the destination and the remaining energy level the next hop owns. The new contribution of this work is to add a third metric in the next-hop selection process, that is, the risk level of a node defined as the amount of risk the sender may encounter by selecting a particular node as a next hop. The risk value a sender knows about a node reflects the "trustworthiness" that it has towards that node.

FUTURE RESEARCH DIRECTIONS

Recent research work focuses on energy-aware design and efficient communication and net-

working within the WSN. On the physical layer level, techniques for low-power hardware design, overcoming signal propagation, and optimized modulation schemes are of great interest. Another very important area of open research is the design of energy-aware and efficient medium access control protocol for enhanced WSN performance and prolonged network lifetime. On the network level, new integrated identity and behavior trust aware routing algorithms that are tailored for operation given the limitations of the WSN are necessary. Finally, at the application layer, protocols necessary for sensor management, task assignment and data advertisement, and sensor query and data decimation are being developed.

Node mobility is an important issue to be considered when developing secure routing protocols. Most of the current protocols assume that the senor nodes and the base stations are stationary. However, there might be situations such as battle environments where the base station and possibly the sensors need to be mobile. In such cases, frequent update of the position of the base station and sensor nodes and propagation of that information through the network and rekeying operation may excessively drain the energy of nodes. New secure routing algorithms are needed in order to handle the overhead of mobility, rekeying, and topology changes in such an energy-constrained environment. A feature that is important in every routing protocol is to adapt to topology changes very quickly and to maintain the network functions.

One aspect of sensor networks that complicates the design of a secure routing protocol is in network aggregation. In WSNs, in-network processing makes end-to-end security mechanisms harder to deploy because intermediate nodes need direct access to the contents of the messages. Finding efficiently and optimally the processing points in WSNs is still an open research issue.

There are not many published work on the general intrusion detection techniques for wireless sensor networks. There are some works on intrusion detection targeted for specific kind of attacks. Wireless sensor networks require a solution that is fully distributed and inexpensive in terms of communication, energy, and memory requirements. In order to look for anomalies, applications and typical threat models must be understood. It is particularly important for researchers and practitioners to understand how cooperating adversaries might attack the system. The promising approach for decentralized intrusion detection is the use of secure groups. More research is needed to determine better node features addressing specific vulnerabilities and to develop improved detection algorithms taking into account sensor node capabilities.

Novel techniques of network clustering that maximize the network lifetime are also a hot area of research in WSNs (Bandyopadhya & Coyle, 2003). Since sensor nodes are prone to failure, fault tolerance techniques come into the picture to keep the network operating and performing its tasks. Routing techniques that explicitly employ fault tolerance techniques in an efficient manner are still under investigation (Dulman et al., 2003).

Another area which needs extensive research is the study of survivability issues in wireless sensor networks. Survivability of a system can be defined as the capability to fulfill its mission, in a timely manner, and in the presence of intrusions, attacks, accidents, and failures. A framework of survivability model for WSN with software rejuvenation methodology, which is applicable in security, has been proposed by (Kim, Shazzad, and Park (2006).

Most of the currently proposed key management schemes are based on the assumption that all the nodes in the sensor networks are homogeneous and with similar capabilities, such as memory and radio range. It has been found that by applying heterogeneous sensor nodes in a sensor network, the small percentage of more capable sensor nodes can provide an equal level of security, and meanwhile improve the resilience of node compromise. The unbalanced scheme proposed by Traynor, Choi, Cao, Zhu, and La Porta (2004) not only reduces the number of transmissions necessary to establish session-keys but also reduces the effect of both single and multiple node captures. Another area which needs intensive research is the development of path-key establishment phase of key management scheme. Some special protocols combined with routing information may be con-

sidered to achieve the secure and efficient path-key establishment. Furthermore, based on the current research on the coverage and connectivity in the sensor networks, some random distribution model (Bettstetter, 2002) should also be considered when modeling a secure communication model in wireless sensor networks.

An important area which needs extensive research is the development of efficient node monitoring and rating approaches in reputation system-based solutions. Another problem which needs extensive research is a bootstrapping problem in sensor networks. This the startup period which is required to build reputation and trust among nodes in a network in noncryptographic-based solutions and to discover shared keys and perform key-setup among sensor nodes in cryptographic-based solution. Minimizing this startup period to prevent node compromise during bootstrapping is an open issue.

Public-key solutions built upon the pairing-based identity-based cryptography (IBC) is emerging as an alternative (more appropriate than traditional public key cryptography for WSNs) with the efficient hardware implementation of Tate pairing (Barreto, Lynn, & Scott, 2004) on smartcard (Bertoni, Chen, Fragneto, Harrison, & Pelosi, 2005), PDAs (Scott, 2005), and FPGAs (Kerins, Marnane, Popovici, & Barreto, 2005).

Another issue which has triggered a growing debate is on the use of symmetric-key vs. public-key cryptography (PKC) in WSNs. How to modify the public key cryptography and apply it to the key management issues in resource-constrained WSNs is a major challenge. Recent studies show that it is still possible to apply public key cryptography to sensor networks by judiciously selecting right algorithms and associated parameters (Arazi, Elhanany, Arazi, & Qi, 2005; Gaubatz, Kaps, & Sunar, 2004). ECC (Malan, Welsh, & Smith, 2004) is especially attractive for constrained wireless devices because the smaller keys in ECC result in memory, bandwidth, and computational savings. With the advancements of hardware and software, public key infrastructure in WSN is not only possible but also necessary (Gura, Patel, Wander, Eberle, & Shantz, 2004).

CONCLUSION

In this chapter, we have presented a comprehensive treatment of the routing security problem in wireless sensor networks. We have provided an overview of WSN architecture, possible applications, and indicated the special characteristics of wireless sensor networks from routing perspective. We have highlighted the importance of secure routing problem considering the different network aspects and special conditions of WSN. We have provided a detailed analysis of routing threats and attacks that are more specific to routing operation in wireless sensor networks and also indicated possible countermeasure against these attacks. We have provided a comprehensive review and an in-depth discussion of different intrusion prevention and detection techniques, cryptographic-based solutions (with emphasis on key management schemes), and noncryptographic-based solutions (with emphasis on trust and reputation of sensor nodes) for the secure routing problem highlighting their pros and cons. We have also presented some open problems that are currently being researched.

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KEY TERMS

DoS Attack: Any event that decreases or eliminates a network's capacity to perform its expected function is termed as a denial-of-service attack or commonly known as DoS attack.

Intrusion: Can be defined as a set of actions that can lead to an unauthorized access or alteration of a certain system.

Key Management: A scheme to dynamically establish and maintain secure channels among communicating nodes. In wireless sensor networks, a key management scheme must deal with the following important issues: key deployment/key predistribution, key discovery, key establishment/key setup, node addition/rekeying, and node eviction/key revocation.

Reputation System: A type of collaborative filtering algorithm which attempts to determine ratings for a collection of entities, given a collection of opinions that those entities hold about each other.

Routing Attacks: Network layer attacks such as routing information spoofing, alteration or replay, blackhole and selective forwarding attacks, sinkhole attacks, Sybil attacks, wormhole attacks, HELLO flood attacks, and acknowledgement spoofing.

Routing Security: Securing routing operation from attacks in a network by deploying appropriate defense.

Trust: A relationship of reliance. Trust is a prediction of reliance on an action, based on what a node knows about the other node, in the context of wireless sensor networks. The notion of trust is increasingly adopted to predict acceptance of behaviors by others.

Wireless Sensor Network (WSN): A wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants at different locations.

Chapter XXXVII
Localization Security in Wireless Sensor Networks

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ABSTRACT

Localization of sensor nodes is very important for many applications proposed for wireless sensor networks (WSN), such as environment monitoring, geographical routing, and target tracking. Because sensor networks may be deployed in hostile environments, localization approaches can be compromised by many malicious attacks. The adversaries can broadcast corrupted location information; they can jam or modify the transmitting signals between sensors to mislead them to obtain incorrect distance measurements or nonexistent connectivity links. All these malicious attacks will cause sensors not able to or wrongly estimate their locations. In this chapter, we summarize the threat models and provide a comprehensive survey and taxonomy of existing secure localization and verification schemes for wireless sensor networks.

INTRODUCTION

In recent years, the availability of low-cost, low-power, multifunctional, small-size autonomous devices equipped with various sensors has expedited the development of wireless sensor networks (WSN). Wireless sensor networks have both military applications (e.g., battlefield surveillance) and civilian applications (e.g., environment and habitat monitoring, target tracking, seismic detection, smart-home automation, and traffic control). To facilitate the cooperation between sensors and achieve different application goals, network and application protocols such as routing protocol, data

aggregation algorithm, and localization algorithm need to be properly designed.

Among these research issues, localization of sensor nodes is very important to some applications. For example, in environment surveillance applications, a sensor must report its location to the monitoring center when it detects some enemy force (e.g., a tank); in geographical routing protocol, a sensor should know the locations of its neighbors and forwards data packets to the neighbor who is closest to the destination.

Traditional localization approaches require the sensor nodes to equip with expensive global positioning system (GPS) devices, which are not affordable in some cases, especially in large-scale sensor networks. Hence, many localization schemes (Bahl & Padmanabhan, 2000; Bulusu, Heidemann, & Estrin, 2000; Doherty, Pister, & Ghaoui, 2001; Fang, Du, & Ning, 2005; Harter, Hopper, Steggles, Ward, & Webster, 1999; He, Huang, Blum, Stankovic, & Abdelzaher, 2003; Lazos & Poovendran, 2004; Nicolescu & Nath, 2001, 2003; Priyantha, Chakraborty, & Balakrishnan, 2000; Savvides, Han, & Srivastava, 2001; Shang, Ruml, Zhang, & Fromherz, 2003; Smith, Balakrishnan, Goraczko, & Priyantha, 2004) have been proposed. These schemes assume that some special sensor nodes (named anchors) can obtain their absolute locations through GPS device. Thus other sensors can use the measured distance or connectivity information between them and the beacon messages sent from the anchors to calculate their locations.

When sensor networks are deployed in hostile environments, localization approaches are vulnerable to many malicious attacks. For example, the adversaries can compromise a sensor node and send out false location information to disturb the localization of other nodes. Sensor nodes are constrained by limited energy resources, memory resource, computation ability, and communication bandwidth, therefore, traditional cryptography mechanisms such as a public key system cannot be applied to wireless sensor networks. Moreover, localization approaches utilize the physical features of the transmitting signals between sensors (e.g., transmitting time or signal strength), thus they are vulnerable to many localization-specific attacks (e.g., distance-modification attack) that cannot be prevented by traditional security mechanisms. All these attacks can cause the sensors to be not able to or wrongly estimate their locations.

In this chapter, we provide a comprehensive survey and taxonomy of existing countermeasures that secure the localization in wireless sensor networks. We classify the secure countermeasures into secure localization schemes, which enhance sensors' attack-resistant ability, and location verification schemes, which verify sensors' locations (accept the correct location estimations and discard the abnormal ones) after the sensors have obtained their locations. We also classify these secure localization (or verification) schemes on whether they use precise (with nanosecond precision) time-measuring hardware, sectored antenna, or not use any special hardware.

The rest of chapter is organized as following: In the following section, we take an overview and give a classification of current localization approaches. We describe the threat models, and we provide the taxonomy of existing secure localization approaches. Finally, we discuss some future trends and conclude the chapter.

BACKGROUND: LOCALIZATION IN WIRELESS SENSOR NETWORKS

In recent years, many localization approaches have been proposed for wireless sensor networks. Before we talk about the security issues, let us take an overview of the localization systems and the techniques involved in different localization approaches.

The most traditional and widely-used localization system is the global positioning system. The earth-based GPS receivers can provide users with location, speed, and time by calculating the distances from at least three satellites. However, it is not feasible to equip the relatively expensive GPS receiver on each node in large scale sensor networks. Most localization algorithms assume that only a fraction of sensor nodes in the field can obtain their locations through GPS receivers (or

through manual configurations). These nodes are called anchors and serve as location references for other nodes to localize. Depending on the availability of such anchors, we classify the localization approaches as anchor-based or anchor-free ones. We also classify them into range-based or range-free ones on whether they require distance measurements between sensors, and centralized or distributed on whether the localization is performed by a computing center or by sensors themselves. The classification is given in Table 1, where "(c)" means that the approach is centralized.

Anchor-Based Range-Based Approaches

In anchor-based localization approaches, some anchors are deployed whose positions are known from GPS device or manual configuration. In range-based approaches, the sensors' locations are determined by using trilateration technique based on the distances between sensors. The trilateration method solves a set of equations and estimates sensor's location that best satisfy the distance constraints (according to some optimization criteria, e.g., least square error criteria). Active Bat (Harter et al., 1999), RADAR (Bahl & Padmanabhan, 2000), AHLoS (Savvides et al., 2001), and SDP (So & Yu, 2005) are all anchor-based range-based approaches. Besides the least mean square criteria, Kalman-filter (KF) and least mean square (LMS) (Smith et al., 2004) can also be applied to obtain the optimal solution for sensors' location.

Anchor-Based Range-Free Approaches

Since range-based approaches require special hardware to measure the distances between sensor nodes, range-free approaches attracted more research interests recently. In anchor-based range-free approaches, no distance measurements are needed and sensors determine their locations using the beacon messages from anchors. Both Active Badge (Want et al., 1992) and Cricket (Priyantha et al., 2000) belong to this category. Centroid method (Bulusu et al., 2000) calculates a sensor's location as the mean value of the locations of anchors from which this sensor hears beacon messages. APIT (He et al., 2003) determines some triangles in which a sensor may reside, and estimates the sensor's location as the overlapping region of theses triangles. SeRLoc (Lazos & Poovendran, 2004) uses sectored antennas equipped on anchors and computes sensor's location as the centroid of the overlapping region of multiple sectors. DV-hop (Nicolescu & Nath, 2001) and DV-based AoA (Nicolescu & Nath, 2003) first obtain the hop

Table 1. Classification of localization approaches

	Range-Based	**Range-Free**
Anchor-Based	**Active Bat(c)** (Harter et al., 1999) **RADAR(c)** (Bahl & Padmanabhan, 2000) **AHLoS** (Savvides, Han, & Srivastava, 2001) **LMS/KF** (Smith et al., 2004) **SDP(c)** (So & Yu, 2005)	**Active Badge(c)** (Want et al., 1992) **Centroid** (Bulusu et al., 2000) **Cricket** (Priyantha et al., 2000) **Convex(c)** (Doherty et al., 2001) **DV-hop** (Nicolescu & Nath, 2001) **DV-based AoA** (Nicolescu & Nath, 2003) **APIT** (He et al., 2003) **Amorphous** (Nagpal, Shrobe, & Bachrach, 2003) **SeRLoc** (Lazos & Poovendran, 2004)
Anchor-Free	**MDS-MAP(c)** (Shang et al., 2003)	**MDS-MAP(c)** (Shang et al., 2003) **Deployment Knowledge** (Fang, Du, & Ning, 2005)

counts from sensors to anchors by flooding through the sensor field, then estimates the average hop distance and translates the hop-count distances to real distances to determine sensors' locations. Amorphous (Nagpal et al., 2003) employs a similar strategy as DV-hop but estimates the average hop distance offline. Convex (Doherty et al., 2001) utilizes a linear programming (LP) method to solve the linear equations and obtain the optimal solutions for the sensors' locations.

Anchor-Free Range-Based Approaches

There are relatively fewer anchor-free range-based localization approaches. One is MDS-MAP (Shang et al., 2003), which is based on multidimensional scaling technique to derive the locations of all sensors. It can also work as a range-free approach when only using the connectivity information between sensors instead of the distance measurements, which may cause some degradations of the localization performance.

Anchor-Free Range-Free Approaches

MDS-MAP (Shang et al., 2003) is a centralized anchor-free range-free localization approach. Besides, Fang et al. (2005) proposed a decentralized approach, which assumed that sensors are deployed in groups and the sensors in the same group can land in different locations following a known probability distribution. With this prior deployment knowledge, a sensor utilizes the observation of the group memberships of its neighbors, and utilizes the maximum likelihood estimation method to determine its location.

THREATS TO LOCALIZATION APPROACHES

Since sensor networks may be deployed in hostile environments, the localization approaches are subject to many malicious attacks. In this section, we classify and discuss the possible attacks launched to the current localization approaches.

Attackers can compromise anchors or sensors and send out false location information. They can jam the communications between sensors and replay the messages, which maes sensors wrongly estimate the time-of-flight value and obtain wrong distance measurements. They can strengthen or weaken the signal strength, which also makes the sensors obtain wrong distance measurements. Finally, the attackers can use a wired link (called wormhole) to transmit messages received from one location and broadcast at the other location, thus making sensors build nonexistent neighboring connectivity, which results in wrong estimations of the sensors' locations.

We can classify the attackers into internal attackers and external attackers. An internal attacker can compromise a sensor, obtain its key materials, and authenticate itself to others. An external attacker cannot obtain any cryptographic secrets or authenticate itself, but it can corrupt the physical features of the communications between sensors, for example, they can corrupt the distance measurements or neighboring connectivity by jamming the communications between sensors. In Table 2, we list the threat models and the corresponding attackers that can launch the threat models. We then describe them in more details in the following subsections.

Fake Location

Fake locations information can be generated by the internal attackers who compromise sensors and authenticate themselves as legitimate ones. The impact of this attack is twofold. First, many location-based applications such as environment monitoring and target tracking will be fooled by the wrong location of some specific events, for example, high-temperature area and location of an enemy tank. Second, other sensors' locations will be polluted if they refer to these fake locations when localizing themselves.

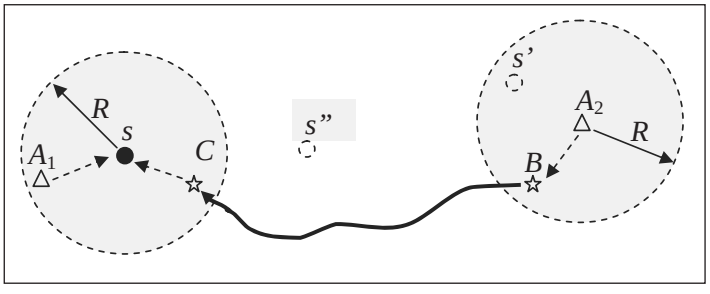
Wormhole

Wormhole attack was first discussed by Hu, Perrig, and Johnson (2003). In the wormhole attack, the

Table 2. Classification of threat models

	Fake Location	Wormhole	Range Englargement	Range Reduction
Internal Attackers	X		X	X
External Attackers		X	X	X

Figure 1. A wormhole attack on sensor localization



adversaries copy the messages heard at one location and replay them at another location.

Figure 1 illustrates how a wormhole attack can damage a sensor's localization. As shown in the figure, sensor *s* can directly hear the beacon message of anchor A1, but not of anchor A2. To attack the localization of s, an adversary establishes a wormhole between position B and C, which are near A2 and *s*, respectively. Then, the adversary records A2's beacon message at position B, transmits it through the wormhole tunnel, and replays it at position C. If *s* determines its location only based on A2's beacon message, it may assume it is near anchor A2 (at some location within the transmission region of A2). If it uses both messages of A1 and A2, it may either believe it is located somewhere between A1 and A2 (e.g., at location *s''*) or it may not be able to determine its location at all because it is not expected to receive the beacon messages from two anchors so far away from each other.

In such a wormhole attack, the adversaries do not need to compromise any sensor or anchor to understand the meaning of the messages, they just copy and transmit the messages through the established wormhole tunnel to corrupt the localization approaches.

Range Enlargement and Reduction

The range modification attacks are detrimental to range-based localization approaches.

(1) If a time-of-flight method is used to estimate distance, external attackers can jam and replay the signal or transmit it through multipaths to prolong the transmitting time (range enlargement attack). Or they can speed-up the signals to shorten the transmitting time (range reduction attack). For example, they transform the ultrasound signal into radio frequency signal whose transmitting speed is faster, and transform the signal back to ultrasound and broadcast the signals at the end point. Internal attackers can fully control the compromised sensors, thus they may hold on to the signal for a short period of time before transmitting to launch a range enlargement attack. (2) If a signal strength method is used to estimate distance, external attacker can jam and strengthen or weaken the signal before replaying it; internal attackers can directly broadcast signals with strengthened or weakened signals.

A TAXONOMY OF SECURE MECHANISMS

In recent years, many secure mechanisms have been proposed to defend against the attacks to localization in wireless sensor networks. We provide a taxonomy in Table 3. Secure location schemes can help the sensors to correctly localize themselves; location verification schemes can detect and discard abnormal locations of sensors after their locations have been determined. We classify these secure mechanisms on whether they use delicate hardware, directional antenna, or no special hardware. In the following subsections, we discuss each category of the secure mechanisms in more details.

Secure Localization Schemes Against Wormholes

Hu et al. (2003) propose the first work called pack leashes to defend against wormhole attacks. In their work, a temporal packet leash is established by restricting an upper bound on the lifetime of a packet. When receiving a packet, the receiver checks if it has been expired and discards the expired packets that are transmitted through wormholes and incur long processing and transmitting time. A geographical packet leash is established by calculating the distance between two sensors' geographical positions. The receiver can recognize the wormhole packets that travel a distance longer than a certain threshold. In the temporal leash, highly precise synchronization (hundreds of nanoseconds) is required, since a radio signal travels at the speed of light and the mutual distance between sensors are of only several meters. In the geographical leash, correct geographical locations are necessary, thus it cannot be used to defend against wormhole attacks that make the sensors' locations not trustworthy.

Hu and Evans (2003) utilize sector antennas equipped on sensors to detect wormholes. They assume that each antenna has N equally divided zones (numbered from 1 to N). A sensor listens to the carrier in omnimode, and receives signals through the zone in which the signal power is maximal. By using a magnetic needle, it can be ensured that the antenna zones of the same number (e.g., zone of number 1) on all sensors face the same direction. In Figure 2, we see that the signals between true neighbors are sent and received in the opposite zones (e.g., Zone 4 and Zone 1). Therefore, if a sensor receives a message in Zone i, and the mes-

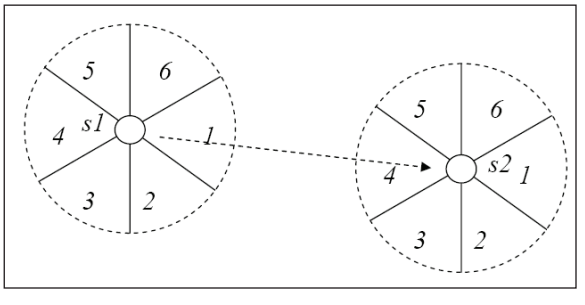
Table 3. A taxonomy of secure localization and location verification schemes

	Secure localization schemes		Location verification schemes
	Against wormholes	Against all attacks	
Delicate hardware required	**Packet Leashes** (Hu et al., 2003)		**Distance-bounding** (Brands & Chaum, 1993) **Claim** (Sastry, Shankar, & Wagner, 2003) **Verifiable Multilateration(L)** (Capkun & Hubaux, 2005) **Covert Base-station** Capkun, Cagalj, & Srivastava, 2006)
Sector antenna required	**Sectored antenna** (Hu & Evans, 2003) **SeRLoc** (Lazos & Poovendran, 2004)		
No special hardware required		**MMSE-Outlier** (Liu, Ning, & Du, 2005) **LMS-Outlier** (Li, Trappe, Zhang, & Nath, 2005) **COTA** (Wei, Yu, & Guan, 2006)	**LAD(L)** (Du, Fang, & Ning, 2005) **PLV** (Ekici, McNair, & Al-Abri, 2006)

sage is sent from Zone j of the sender node, and i and j are not opposite to each other, we can detect that messages may be transmitted through some wormholes. Besides this basic detecting method, the authors propose a verified-neighbor-discovery protocol and a strict-neighbor-discovery protocol to detect the sophisticated wormholes. These protocols require some *potential verifier nodes* to help a sensor to distinguish legitimate neighbors from the wormhole ones. Thus the lack of sufficient verifier nodes will result in the lost of some legitimate connectivity links and degradation of the localization performance.

Lazos and Poovendran (2004) propose another secure localization scheme called SeRLoc that also uses sectored antennas. An anchor transmits different beacons at each antenna sector containing the anchor's location and the angles of the antenna boundary lines. Each sensor determines its location as the center of gravity of the overlapping region of all sectors it hears. During this localization process, wormholes can be detected using two properties: the sector uniqueness property and the communication range violation property. If two sectors of a single anchor are heard, or if two anchors heard by the sensor have a mutual distance greater than 2R (R is the communication range), the sensor can detect that it is under wormhole attacks. After detecting the wormhole, the sensor broadcasts a random nonce and identifies the closest anchor, Li, by the first reply, then takes the center of gravity closest to Li as its estimated location. This technique is named attach to closer locator algorithm (ACLA). One problem of ACLA is that innocent packets may sometimes arrive later than the ones through wormholes because the communications are unreliable in reality and the messages may need to be retransmitted multiple times before the receiver can actually receive them.

Figure 2. Detect wormholes using sector antennas



Secure Localization Schemes Against All Attacks

All malicious attacks to localization including fake locations, wormholes, and range modifications have a common feature: they all provide inconsistent location references, namely, the sending sensor's location and the measured distance between the sender and the receiver are inconsistent. Therefore, some experts suggested using statistical outlier-removing methods to filter out inconsistent references.

Liu et al. (2005) take the mean square error (MSE) as an indicator of the degree of inconsistency among location references. They propose a greedy algorithm that starts with the set of all location references, and each time considers the subsets with one fewer reference and chooses one subset with the least MSE as the input to the next round, until the MSE value drops below a reasonable threshold. This scheme can effectively enhance sensors' attack-resistant ability, but it launches relatively high computation overheads on sensors. Another problem is that it requires benign references to be the majority among all location references, and may not work well when corrupted location references collude together and take a larger percentage (e.g., around 50%) among all references.

Instead of identifying and eliminating inconsistent references before localization, Li et al. (2005) propose a scheme that lives with these inconsistent references and estimates reasonable locations for sensors using least median of the squares (LMS) technique. LMS is one of the most commonly used robust fitting algorithms and can tolerate up to 50% outliers among the total references. Since the exact LMS solutions are computationally prohibitive, the authors adopted an efficient alternative technique (Rousseeuw & Leroy, 2003) to first get several candidate reference subsets, then choose the one with the least median squares to estimate a sensor's location.

Both of the above schemes try to prevent sensors from wrongly localizing themselves, however, when a sensor fails to filter out the inconsistent references, its corrupted location would "pollute" the localization of many downstream sensors and cascade through the entire sensor network. Wei, Yu, and Guan (2006) propose a scheme named COTA that uses confidence tags to identify spurious localizations of sensors. COTA consists of a tag generation process and a reference filtering process. In the tag generation phase, two methods (the statistic indicator and the geographical indicator) can be used to calculate the sensors' confidence tags based on the positions of their neighbors, distance measurements, and the confidence tags of their neighbors. In the reference filtering phase, bad references can be filtered out by comparing their confidence tags to the absolute and relative metrics. COTA can effectively prevent the proliferation of location errors in the sensor field.

Location Verification Schemes

Although many secure localization schemes have been proposed to provide robust localization performance, they require special hardware or assume some limitations on the adversaries' abilities, and cannot guarantee that all sensors can calculate correct location estimations. Moreover, a compromised sensor (internal attacker) can directly report corrupted locations to the base station; meanwhile it provides a correct location to its neighbors and cannot be detected. These corrupted locations can cause severe consequences to many location-based applications. For example, wrong locations of enemy force will make the surveillance center not able to locate or track the real target, and thus the location verification is a necessary second-line to defend against the adversaries. Note that some verification schemes can also be used as secure localization schemes if sensors' locations have not been determined, and we denote them by "(L)" in Table 3.

Verification Using Special Hardware

The location verification problem was first introduced by Sastry et al. (2003), where the authors propose the echo protocol to verify if a device is inside some specific region (e.g., a room or a football stadium) to facilitate location-based access control. Their protocol is very simple in that the verifier node sends a packet containing a nonce using RF and the device echoes the packet back using ultrasound. Then by checking the packet transmission time and the processing delay, the verifier can verify if the device locates inside the circle region centered at the verifier.

If RF time-of-flight method can be used to measure distance, distance-bounding protocol (Brands & Chaum, 1993) can upper bound the measured distance from one device to another. The important assumption of this protocol is that the device can bound its xor processing to a few nanoseconds and the verifier can measure time with nanosecond precision. Based on this distance-bounding protocol, Capkun and Hubaux (2005) propose a location verification scheme for wireless sensor networks using a verifiable multilateration (VM) technique. The rationale behind VM technique is that when a sensor claims to locate somewhere within a triangle region formed by three verifiers, then its location can be verified only when all three distances from the sensor to the verifiers are consistent with the calculated ones. The limitations of the VM technique are the requirement of delicate hardware to perform distance-bounding protocol and the requirement of dense deployment of verifiers.

Lazos, Poovendran, and Capkun (2005) propose a secure localization and verification system called ROPE, which combines the secure properties of the verifiable multilateration technique (Capkun & Hubaux, 2005) and SeRLoc (Lazos & Poovendran, 2004).

Capkun et al. (2006) propose a verification scheme using covert base stations. The covert base stations (CBS) are silent to the on-going communications and their positions are only known to the verification infrastructure. Upon receiving location messages from a sensor, several CBS cooperate (through wired links) and check if their location is consistent with the difference of time-of-arrival to each CBS. Because sensors do not know the positions of CBS, their success rate to achieve consistency through guessing is

very small. A mobile base station (MBS) can also play the role of verifier, by sending a verification request from one location, moving, and waiting for the response at a different location. Therefore, at the time of performing verification, a sensor does not know the positions of the MBS.

Verification Without Special Hardware

Unlike other verification schemes that use some special hardware, Du et al. (2005) propose a scheme that verifies sensors' locations by checking the consistency of the locations with the deployment knowledge. They assume that all sensors are deployed in groups (each group has a unique group ID) following a known probability distribution. A sensor's location can be verified only when its neighborhood observation is consistent with that derived from the deployment knowledge. The difference between this scheme and the previous works is that in this scheme, the sensors are verified if their locations are within an anomaly degree from their true locations, rather than exactly at the true locations.

Recently, Ekici et al. (2006) proposed probabilistic a location verification (PLV) algorithm to verify sensors' locations in densely deployed sensor networks. PLV explores the probabilistic relation between the number of hops a packet traverses to reach a destination and the Euclidean distance between source and destination. Then the verifier can determine plausibility (between 0 and 1) and create a trust level for each sensor's location claim.

FUTURE TRENDS

Although various secure mechanisms have been proposed for localization in wireless sensor networks, there is still a large space for future improvements.

First, very few works have been done to secure range-free localization approaches which deserve more research efforts. For example, in DV-hop approach, if the adversaries compromise a single node and send out a false hop count, then all down-steaming nodes will be influenced and estimate false hop counts from them to the anchor, resulting in a biased estimation of the average hop-distance.

Another issue is that current location verification schemes either verify if a sensor exactly locates at its claimed location, or verify if it locates within the anomaly degree of its true location. However, verification regions can be arbitrary and should be related to the specific application. For example, in a military surveillance application, the monitoring center decides to project a missile at the location reported by the sensor who detects the enemy force, thus it should determine a specific verification region in which the detecting sensor should reside to guarantee that the target can be destroyed.

CONCLUSION

In this chapter, we provide a taxonomy of the research efforts devoted to secure localization in wireless sensor networks. We classify them into secure localization schemes that aim to provide correct location estimations for sensors at the front-line, and location verification schemes that aim to detect abnormal locations of sensors at the second-line, that is, after sensors' locations have been determined using any other (insecure or secure) localization approaches. We also classify the security localization mechanisms on whether they require any special hardware. Generally, localization for sensor networks becomes more robust with the availability of more advanced hardware, for example, sectored antennas, fast processing hardware, or even nanosecond-precision clocks. If there is no such special hardware, other information such as deployment knowledge is needed to detect the inconsistent information injected by adversaries.

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KEY TERMS

Anchors: Anchors are special sensors that know their locations before localization through a GPS device equipped on them or through manual configurations.

Localization: Localization in wireless sensor networks is the process that all sensors obtain their relative or absolute locations, by themselves or by network computing center.

Location Verification: Location verification in wireless sensor networks is the process that correctly estimated locations of sensors can be verified and corrupted locations can be detected.

Range-Based/Range-Free: A localization approach is range-based (or range-free) if it does (or does not) use the measured distance between sensors to estimation their locations.

Secure Localization: Secure localization in wireless sensor networks is the process that sensors can obtain their locations in the presence of malicious attacks.

Wireless Sensor Network (WSN): A wireless sensor network (WSN) is a wireless network consisting of autonomous devices that cooperatively monitor environmental conditions, such as temperature, sound, pollutants, and so forth.

Wormholes: Wormholes in wireless sensor networks are nonexisting communication tunnels (usually wired links) created by adversaries. The messages received at one end of a wormhole can be transmitted through the tunnel, and broadcasted at the other end.

Chapter XXXVIII
Resilience Against False Data Injection Attack in Wireless Sensor Networks

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ABSTRACT

One of the severe security threats in wireless sensor network is false data injection attack, that is, the compromised sensors forge the events that do not occur. To defend against false data injection attack, six en-route filtering schemes in a homogeneous sensor network are described. Furthermore, one sink filtering scheme in a heterogeneous sensor network is also presented. We find that deploying heterogeneous nodes in a sensor network is an attractive approach because of its potential to increase network lifetime, reliability, and resiliency.

INTRODUCTION

Wireless sensor networks (WSN) usually consist of a large number of inexpensive and small nodes with sensing, data processing, and communication capabilities. These nodes are densely deployed in a region of interest and collaborate to accomplish a common task, such as environmental monitoring, military surveillance, and industry process control. Distinguished from traditional wireless networks and ad hoc networks, WSN are featured in dense node deployment, unreliable sensor node, frequent topology change, limited power resource, and limited computation capacity, restricted memory space. These unique characteristics and constraints present many new challenges to the design and implementation of WSN.

For many mission-critical applications, the sensor nodes are deployed in an unattended or often hostile environment and WSN face many security and privacy challenges. One challenge is that when deployed in hostile environments, sensor nodes may be captured or compromised by the adversaries. Then the adversaries can obtain the secret keys

stored in the compromised nodes, and misuse them to launch *insider attacks*. Therefore, a nonresilient security protection scheme will exhibit a *threshold breakdown* problem. That is, the design is secure against t or less compromised nodes, but once more than t nodes are compromised the security design completely breaks down, where t is a fixed threshold. Since in reality nobody can prevent an attacker from compromising more than t nodes, such a security protection solution cannot meet the resilience requirement. Our expectation in terms of resilience is that, compromising t nodes in a certain area can only enable an adversary to forge nonexisting events in that specific area, rather than any other location at all. Put in other words, for an attacker, the only way to generate a valid report on a nonexisting event happening in a certain area is to compromise t nodes in that area.

In this chapter, we overview several schemes that have been proposed to defend against *compromised nodes*. We will show that several schemes are only resilient against a small, fixed number of compromised nodes with threshold breakdown problems, while subsequent schemes partially and completely solve the threshold breakdown problems.

The rest of this chapter is organized as follows. In the next section, we introduce the background. Several en-route filtering schemes in a homogeneous sensor network are presented. Furthermore, a sink filtering scheme in a heterogeneous sensor network is shown. Finally, the last section concludes the chapter.

BACKGROUND

False Data Injection Attacks

We consider a sensor network, which consist of hundreds or thousands of low-cost sensors. Each sensor senses and collects data from the environment. There is at least one base station (or *sink*), which is typically a resource-abundant computer equipped with sufficient computation and storage capabilities. We assume that the sensor nodes are deployed in a high density, so that once an event happens it can be detected by multiple sensors. However, it is inefficient and also unnecessary for every sensor node to report their raw data to the sink node, because: (1) every data packet usually needs to travel many hops (e.g., tens or event longer) to reach the sink; (2) each sensor node is often constrained by scarce resources in memory, computation, communication, and battery; and (3) in many cases there is high redundancy in the raw data. Hence, raw data are often fused and aggregated locally, and only the aggregated information is returned to the sink. In such a setting, certain nodes in the sensor network will function as *cluster heads* (*CHs*), to collect the raw sensing data from the sensors, process it locally, and return the aggregation report to the sink. Once the sink receives an event report, it may take action accordingly.

Unfortunately, the above event detection and reporting process can be seriously threatened by *false data injection attacks*. As we stated above, sensors are usually deployed in unattended or even hostile environments, and an adversary may capture or compromise sensor nodes. Once this happens, the compromised nodes can easily inject false data reports of nonexisting events. Even worse, when an adversary compromises more nodes and combines all the obtained secret keys, the adversary can freely forge the event reports which not only "happen" at the locations where the nodes are compromised, but also at *arbitrary* locations in the field. These fabricated reports not only produce false alarms (and lead to *false positives*), but also waste valuable network resources, such as energy and bandwidth, when delivering the forged reports to the base station. Therefore, it is important to design an effective filtering scheme to defend against such attacks and minimize their impacts.

In this chapter, we consider the following *threat* model. The attacker may compromise multiple sensor nodes in the network, but cannot compromise the sink. Once a sensor node is compromised, the attacker can obtain all secret keys, data, and codes stored in the sensor. Whenever more nodes are compromised, the attacker can combine all the secret keys that have obtained, and can also load a compromised node with the secret keys obtained

from other compromised nodes. We also assume that the attacker cannot successfully compromise a node during the short deployment phase.

Besides report fabrication attack, there are various other attacks in wireless sensor networks. For example, a compromised node may simply not report an event that occurs (which leads to *false negative*), or a compromised node replays a legitimate report, and so forth. However, these threats are addressed in other related work and not the focus of this chapter. Instead, in this chapter we overview several schemes that have been proposed to reduce *false positive*, that is, prevent an attacker from fabricating reports about events that do not occur. Two main design goals of these schemes are summarized as follows:

1. **Resilience against a large number of compromised nodes:** A good protection scheme is expected to degrade gracefully as the number of compromised sensor increases, without the threshold breakdown problem.
2. **Adaptive to dynamic topology:** The scheme can deal with dynamic topology of sensor networks and is scalable for large-scale sensor networks.

En-Route Filtering Framework

Statistic en-route filtering mechanism (SEF) (Ye, Luo, Lu, & Zhang, 2004) is the first effort that addresses false data injection attacks in the presence of compromised sensors, where an en-route filtering framework was originally proposed. The en-route filtering framework has three components: report generation using message authentication codes (MACs), en-route filtering, and sink verification.

Report Generation Using MACs

To generate a valid report, multiple (say m, where $m > 1$) nodes detect the event simultaneously and agree on the content of the event report. To be forwarded by intermediate nodes and accepted by the sink, each valid report must carry m MACs; each MAC is generated by the sensing node that detects the event. Each sensor stores a few symmetric secret keys, and the MAC is generated by using one of the secret keys.

En-Route Filtering

By using a suitable key assignment scheme, any intermediate node is able to verify the report with certain probability or deterministically. Whenever an intermediate node receives a report, it first checks whether the report carries m distinct MACs; it then check if itself stores a same key with the sensing node. If yes, it checks whether the carried MAC is the same as the MAC it computes via its locally stored key. It drops the report when any of these checks fails. Otherwise (i.e., it does not have any of the keys or the MACs are correct), it forwards the reports as usual. Notice that though the filtering power of any single node is limited, the collective filtering power along the forwarding path is significant. The more hops a forged report travels, the higher chance it is dropped en-route.

Sink Verification

The en-route filtering performed by the intermediate nodes may be probabilistic in nature, thus cannot guarantee to detect and drop all forged reports. The sink serves as the final guard in rejecting any escaping ones. Because the sink knows all the keys, it can verify each MAC carried in a report. On the basis of the number of correct MACs each report carries, the sink decides whether to accept the event or not.

Besides a SEF scheme, five more designs including interleaved hop-by-hop authentication (IHA) (Zhu, Setia, Jajodia, & Ning, 2004), commutative cipher-based en-route filtering (CCEF) (Yang & Lu, 2004), location-based resilient security (LBRS) (Yang, Ye, Yuan, Lu, & Arbaugh, 2005), location-aware end-to-end data security (LEDS) (Ren, Lou, & Zhang, 2006), and dynamic en-route filtering (DEF) (Yu & Guan, 2006) are all specific instances within the above framework. Based on the above framework, these five proposals have adopted different key management schemes, which immediately lead to different resilience behavior of their designs. We will describe their methodologies in details in the subsequent sections.

SCHEMES IN EN-ROUTE FILTERING FRAMEWORK

Statistic En-Route Filtering

Methodology

In statistic en-route filtering (Ye et al., 2004), there is a global key pool which is divided into multiple T nonoverlapping partitions. Before deployment, each node randomly selects a few keys from a single partition, and is then loaded with these keys and associated key indices. Once an event occurs, each sensing node generates a MAC by using a key in a different partition. The cluster head (CH) node collects the MACs and attaches them to the report. Any intermediate node has a same predetermined probability to detect and filter false reports, and hence SEF filters the forged reports en-route in a probabilistic manner. The sink can always verify every report because it knows the entire key pool. As a result, most of the forged reports are quickly dropped by the forwarding nodes, and the few escaping ones are further rejected at the sink.

Features

First, SEF suffers from the threshold breakdown problem. Second, SEF is independent of dynamic topology changes of sensor networks, and hence is robust against node failures and routing path changes.

Interleaved Hop-by-Hop Authentication

Methodology

Distinguished from SEF, interleaved hop-by-hop authentication (Zhu et al., 2004) verifies the reports in a deterministic and *an interleaved, hop-by-hop* fashion. In the deployment phase, each node is preloaded with a unique ID and keying materials that can allow it to establish a pair-wise key with another node. The nodes form multiple clusters and each cluster has at least (t + 1) nodes, where t is a design parameter. Each cluster head discovers a path to the sink. Along the path, two nodes that are (t + 1) hops away are *associated* by establishing a pair-wise key. Upon an event, each detecting node computes two MACs, one using its key shared with the sink and the other using its pair-wise key shared with its downstream associated node. The cluster head sends out a final report that carries the MACs from (t+ 1) detecting nodes. In the en-route filtering phase, each forwarding node verifies the MAC from its upstream associated node. Upon successful verification, it replaces the old MAC with a new one using its pair-wise key shared with its downstream associated node. The sink performs a final verification on the report. IHA guarantees that if no more than t nodes are compromised, the base station will detect any false data packets injected by the compromised sensors.

Features

First, IHA suffers from threshold breakdown problem, similarly to SEF. Second, since IHA requires that the messages transmitted from the base station to a cluster head and from the cluster head to the base station follow the same fixed path, IHA scheme is not suitable for the sensor networks with dynamic topology.

Commutative Cipher-Based En-Route Filtering

As we discussed above, both SEF and IHA schemes suffer from a threshold breakdown problem. To solve this problem, a commutative cipher-based en-route filtering scheme (Yang & Lu, 2004) was presented on the basis of public-key algorithms.

Methodology

CCEF exploits the typical operational mode of query-response in sensor networks, and installs security states in the nodes in an on-demand manner. Specifically, in CCEF, each node has a unique ID and is preloaded with a unique node key before deployment. When reports are needed, the base station sends an encrypted session key

to the desired cluster head and a witness key in plain-text to all forwarding nodes along the path, through a query message. A legitimate report is endorsed by *a node MAC* jointly generated by the detecting nodes using their node keys, and *a session MAC* generated by the source node using the session key. Through the usage of a commutative cipher, a forwarding node can use the witness key to verify *the session MAC*, without knowing the session key, and drop the fabricated reports. The base station further verifies *the node MAC* in the report that it receives, and refreshes the session key upon detection of compromised nodes.

Features

First, CCEF solves the threshold break down problem. Second, CCEF suffers the dynamic topology problem, similarly to IHA scheme, since it requires the same fixed path for messages in both directions between the base station and the cluster head. Third, CCEF uses the commutative ciphers that are based on public-key algorithms, which have been reported not suitable for sensor networks (Eschenauer & Gligor, 2002).

Location-Based Resilient Security

To mitigate the threshold breakdown problem identified in IHA and SEF schemes, a location-based resilient security scheme (Yang et al., 2005) was proposed which exploited a location-based approach as the fundamental mechanism.

Methodology

In LBRS, the terrain is divided into a geographic grid and binds multiple keys to each cell on it. Such keys are termed as *location-binding keys.* Each node stores two types of keys. The first type is for the local cells within its sensing range, called *sensing cells.* Each node stores *one* key for each of its sensing cells. Such keys are used to endorse events detected in those cells. The second type is for a few randomly chosen remote cells, called *verifiable cells*. Each node also stores *one* key for each of its verifiable cells. Such keys are used to verify events claimed to happen in those cells. Each legitimate report carries *m* distinct MACs, jointly generated by the detecting nodes using the keys bound to the event's cell. When an intermediate node receives a report, it retrieves the event's location from the report and checks whether the location is in one of its verifiable cells. If so, it checks whether it has one of the keys hose indices are carried in the report. If it has such a key, it recomputes the MAC and compares to the carried one. If the two MACs do not match, the report is dropped. Otherwise, it forwards the report. The sink performs final verification on the received reports. It knows all location-binding keys, thus able to verify every MAC in the report.

Features

First, compared with SEF and IHA schemes, LBRS partly solves the threshold breakdown problem, since compromising a certain number of nodes only enables the attacker to fabricate events "appearing" at certain areas without being detected. However, it is still far from achieving the *expected* data authenticity requirement: to generate a valid report on a nonexisting event happening in a certain area, the only way is to compromise *T* nodes in that area, and otherwise impossible. Second, LBRS is suitable for the sensor networks with dynamic topology.

Location-Aware End-to-End Data Security

Later on, Ren et al. (2006) came up with a location-aware end-to-end data security to address the vulnerabilities in existing security designs, by exploiting the static and location-aware nature of WSNs.

Methodology

In LEDS, each node computes three different types of location-aware keys: (a) two *unique secret keys* shared between the node and the sink and used to provide node-to-sink authentication; (b) one *cell key* shared with other nodes in the same cell that

is used to provide data confidentiality; and (c) a set of *authentication keys* shared with the nodes in its *report-auth cells* and used to provide cell-to-cell authentication and en-route bogus data filtering. All these keys are computed by each node locally and independently. In addition, LEDS adopts a (t, T) threshold linear secret sharing scheme (LSSS) so that the sink can recover the original report from any t out of T legitimate report shares. Moreover, LEDS adopts a one-to-many data forwarding approach, that is, all reports in LEDS can be authenticated by multiple next-hop nodes independently so that no reports could be dropped by a single node(s).

Features

First, LEDS meets the expected requirement in terms of resilience, with totally solving the threshold breakdown problem. Second, LEDS is suitable for the sensor networks with dynamic topology.

Dynamic En-Route Filtering

At the meantime, Yu et al. (2006) presente a dynamic en-route filtering.

Methodology

In DEF (Yu et al., 2006), a legitimate report is endorsed by multiple sensing nodes using their own authentication keys generated from one-way hash chains. A cluster head (CH) uses a *hill climbing* approach to disseminate the authentication keys of sensing nodes to the forwarding nodes along multiple paths towards the base station. In filtering phase, each forwarding node validates the authenticity of the reports and drops those false ones.

Features

First, compared with SEF and IHA schemes, DEF can tolerate a larger number of compromised nodes. However, DEF scheme still cannot meet the expected requirement in terms of resilience, as LEDS does. Second, LEDS can deal with dynamic topology of sensor networks; but the overhead incurred (on disseminating the authentication keys to forwarding nodes) is high. Third, as the authors discussed in the chapter, LEDS raises some new types of attacks specific to its scheme.

SCHEMES IN HETEROGENEOUS SENSOR NETWORKS

In the previous section, we looked at some of the security protection schemes in homogeneous sensor networks. However, there is another class of sensor networks, heterogeneous sensor networks, which use two or more type of nodes. It is known that the presence of heterogeneous nodes in a sensor network helps to increase network lifetime and reliability. In this section, we present the design of a sink filtering scheme (SFS) (Ma, 2006a, 2006b) in a heterogeneous network, showing that the presence of heterogeneous nodes in a sensor network also helps to improve the resiliency.

Model of a Heterogeneous Sensor Network

We consider a heterogeneous sensor network where two types of sensors are deployed: basic sensor and cluster head. A basic sensor is simple, inexpensive and power-limited, while a CH has more capabilities on processing and communication, richer power supply, and is more compromise-resilient.

We regard a target deployment area as a two-dimensional square region with size A^2. The sink is located at the center (0, 0). The deployment area is divided into C equal size grids (i.e., clusters), with each grid's size as a^2. The basic sensors are uniformly distributed across the entire deployment area. Without loss of generality, we assume that each CH is deployed at the center of each grid. Each basic sensor is assigned to the nearest CH. Every basic sensor and CH has a unique identification (ID).

Sink Filtering Scheme (SFS)

The two types of sensors and sink node implement different tasks in SFS. A basic sensor senses events and provides its CH a proof for any aggregation

report it has agreed. A CH collects raw sensing data from basic sensors, generates an aggregation report, and relays the report to the sink node. A sink node checks the validity of the carried MACs in an aggregation report and filters out the forged report.

Methodology

We assume that the basic sensors are deployed in a high density. Once a real event occurs, *n* basic sensors within the sensing range can sense it. Instead of communicating directly with the sink, each basic sensor only communicates with its CH. Each CH collects raw sensing data from the basic sensors within the cluster, generates an aggregation report, and then relays the report to the sink node. Since the average number of hops each report has to travel from a CH to the sink in *heterogeneous* sensor networks is definitely much smaller than that in *homogeneous* sensor networks, the design is more energy-saving, efficient, and scalable.

The key management for the clusters of heterogeneous sensor network is as follows. (a) Before deployment, each sensor (either a basic sensor or a CH) shares a secret key with the sink. (b) We assume the neighborhood relationship among CHs is known in advance. Before deployment, each CH simply preloads eight pair-wise keys with its eight immediate neighboring CHs, respectively. The CHs, therefore, organize themselves into a static ad hoc network. (c) Upon deployment, each basic sensor establishes a pair-wise key with its one-hop neighboring basic sensors; the one-hop pair-wise key establishment scheme in LEAP (Zhu, Setia, & Jajodia, 2003) is adopted to achieve this goal. (d) Upon deployment, each CH establishes a pair-wise key with every basic sensor within its cluster; the one-hop (or multi-hop whenever a basic sensor cannot reach its CH in a single hop) pair-wise key establishment scheme in LEAP (Zhu et al., 2003) is used for this purpose.

Features

First, SFS meets the expected requirement in terms of resilience, with totally solving the threshold breakdown problem. Second, SFS is adaptive to the dynamic topology. Third, compared with all the schemes in homogeneous sensor networks, SFS in heterogeneous sensor networks is more efficient and scalable. Interested readers may refer works by Ma (2006a, 2006b) for more details on resiliency study and overhead evaluation.

CONCLUSION

In this chapter, we presented six en-route filtering schemes in a homogeneous sensor network, including statistic en-route filtering (SEF), interleaved hop-by-hop authentication (IHA), commutative cipher-based en-route filtering (CCEF), location-based resilient security (LBRS), location-aware end-to-end data security (LEDS), and dynamic en-route filtering (DEF). Furthermore, a sink filtering scheme in a heterogeneous sensor network is also introduced. Our study demonstrates that exploiting heterogeneity in sensor networks also helps to improve the resiliency.

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KEY TERMS

Aggregation Report: A data structure that synthesizes the state of the phenomena that the wireless sensor network is monitoring.

Compromised Nodes: Nodes on which an attacker has gained control after network deployment.

False Data Injection Attack: The type of attack when the compromised sensors forge the events that do not occur.

Key Management: The process of managing key materials (e.g., key generation, key distribution, etc.) in a cryptosystem.

Message Authentication Code (MAC): It is a short piece of information used to authenticate a message.

Threshold Breakdown Problem: We say a security design has threshold breakdown problem if the design is secure against t or less compromised nodes, but once more than t nodes are compromised the security design completely breaks down, where t is a fixed threshold.

Wireless Sensor Network (WSN): The wireless networks consisting of small sensors that cooperatively monitor environmental conditions, such as temperature, humidity, and so forth.

Chapter XXXIX
Survivability of Sensors with Key and Trust Management

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ABSTRACT

Weiser (1991) envisioned ubiquitous computing with computing and communicating entities woven into the fabrics of every day life. This chapter deals with the survivability of ambient resource-constrained wireless computing nodes, from fixed sensor network nodes to small devices carried out by roaming entities, for example, as part of a personal area network of a moving person. First, we review the assets that need to be protected, especially the energy of these unplugged devices. There are also a number of specific attacks that are described, for example, direct physical attacks are facilitated by the disappearing security perimeter. Finally, we survey the protection mechanisms that have been proposed with an emphasis on cryptographic keying material and trust management.

INTRODUCTION

Weiser (1991) envisioned a ubiquitous computing world where intelligent computing and communicating devices are pervasive and woven into the fabrics of every day artifacts. His vision is being materialised: the market of large scale sensors and hand-held devices networks has been gaining momentum. However, one may question whether or not these computing and communicating entities will be able to survive in an open environment. These computing entities are no more protected by a physical security perimeter; foreign, potentially malicious, entities can tamper with them. Another challenge for the real deployment of these networks of sensors and portable devices is to provide them

with enough energy for long term functioning because it is assumed that they are unplugged from the main electrical power supply and can rarely recharge themselves by this means. Any action carried out by these entities depletes their energy. In addition to being resource-constrained in terms of energy, these entities are resource-constrained in terms of memory and processing, which limit what they can do, especially when these entities are small, such as the sensors deployed in sensors networks.

Usually, sensors are performing two important types of actions or tasks: they have to sense the environment and to send information to a specific target entity, sometimes called sink. For example, the sink may be an Internet gateway that will propagate the information for persistent storage and analysis. Security problems exist both when messages are generated and when they are relayed. Working most of the time in an unattended environment without tamper-proof hardware makes the sensors very vulnerable to attacks.

Generally, mobile ad hoc networks (MANETs) are thought to be composed of nodes bigger than the sensors of sensors networks. Also, whereas sensors are considered (after their deployment) rather fixed concerning their location, MANETs imply that the nodes move. If we assume that the MANET nodes are also unplugged from the main power supply, the nodes have also limited energy. Another difference between sensors and MANET nodes is that instead of just having to sense and forward simple information, MANET nodes are expected to run much more complicated operations that surely require more energy than simple tasks. In this chapter, we consider all ad hoc networks where the wireless nodes are resource-constrained, especially in terms of energy. Thus, as introduced above, the nodes may go from the tiny fixed deployed sensor to the mobile unplugged mobile device.

In this chapter, we first survey the different assets of these entities and then delve into specific attacks on these assets. We present further two main protection mechanisms: cryptographic keying material and evidence-based trust management. Finally, we discuss future trends and draw our conclusion.

BACKGROUND ASPECTS OF NODES SURVIVABILITY

In this section, we first discuss what we mean by nodes survivability, their assets, and especially their energy. Then, we focus on the routing asset, which is an important asset that enables the nodes to communicate beyond their own wireless communication range. It shows that the routing has been initially engineered without attackers in mind, which is also the case for most of the other enabling mechanisms and assets. However, there are a number of attacks that can be carried out on these assets. We survey them at the end of the section.

Node(s) Survivability

First, it is important to note we use the plural in the heading of this section, *nodes survivability,* because it emphasises that the scope of the node's mission may span more than one node. On one hand, it may be a scenario where the survivability of the node itself is more important than the survivability of the other nodes. For example, a user who carries a mobile phone in the mountains may be selfish and would not bother forwarding the messages of other users as they are met on the way to the top of the mountain. The forwarding of a message from another user would deplete the energy of the mobile phone and endanger the survivability of the device and its mission lifetime. On the other hand, the mission may be that the majority of the nodes survive at the expense of the survival of one specific node. It is usually the case in sensors networks where the goal is to sense and monitor a region thanks to the collaboration of many nodes. If a part of the monitored region is quite active, it is possible that the nodes in this active region take over the work of another node, for example, to forward the sensed information in order to maximise the lifetime of the monitoring of the whole region. That type of scenario requires that there is some sort of control on the nodes; an authority is needed to guarantee that the nodes will collaborate and follow the rules. For example, in a military environment, the nodes that are deployed

are configured before the deployment and we can assume that they will all follow the rules (until they are captured or they fail). A military environment is said to be a controlled environment, its extreme being an open environment where every node is free to behave as it wishes. In the middle of these extremes, there are scenarios where a selfish node may increase its lifetime by sporadically helping other nodes: the nodes being interdependent.

The Assets Underlying the Survivability

As explained in the previous subsection, the first type of asset underlying the survivability is the survivability of the node or the survivability of the network of nodes. In interdependent settings, the neighbouring nodes are an asset that enables the node to achieve more than what it could achieve alone. An underlying asset is the trustworthiness of these neighbouring nodes. The node may be able to choose or influence whose nodes are its neighbours, for example, by moving to another location or by mere selection (the third section explains how evidence-based trust management can be used to optimise the selection process). In sensor networks, it is less often assumed that new nodes can be added after the initial deployment of the nodes. Sensors are mainly used to monitor the characteristics of a specific fixed area or targets. However, in MANET scenarios, when the nodes correspond to devices carried by people, it is clear that the nodes can come and go as the people roam from place to place. If the adjunct nodes and their location can be chosen, the survivability of the network of nodes may be prolonged. All the nodes may participate for the survivability of the network of nodes. Therefore, the nodes' participation can be considered as an asset.

Another asset for a node is to be highly tamper-proof. However, as said above, nodes in open environments can be captured and highly tamper-proof hardware may be too costly. An asset may be the possibility to communicate the evidence of tampering, for example, an alert being sent at time of capture or creating some form of tamper-evidence.

Besides being captured by an adversary and removed from the network, the lifetime of the node and its mission mainly depend on its consumption of energy. The design of the node is an inherent asset of the node because both hardware and software designs may end up in consuming more or less energy. Current sensor nodes are battery-enabled devices. The energy consumption of a sensor is due to the computation and the communication modules. Energy is depleted mainly by the communication module. Radio transmission consumes most of the energy spent for security mechanisms and encryption only consumes 3% (Hwang, Lai, & Verbauwhede, 2004). Thus, minimising security transmission is important with regard to energy saving. However, sensors are constrained devices and the security mechanisms available for conventional networks are not suitable due to their limited computational, memory, and energy resources. They are often deployed in hostile environments with no physical access to nodes after deployment. Thus, the sensor lifetime is limited by the initial energy of the battery. Different energy harvesting mechanisms are being researched for sensors, such as the use of solar cells, but they are still not very common. The user's mobile computing devices like personal digital assistants and mobile phones are also battery-powered but they can be more easily recharged.

While energy recharging and harvesting mechanisms are put in place, the nodes need energy saving mechanisms. Usually, energy saving mechanisms are based on the difference of energy consumption between the active and the idle states. Energy is saved by minimising the fraction of time while the device is active. These energy saving mechanisms are normally targeting the subsystem of the device that has the greatest difference between the energy consumption of the two states. Once no application is running on the device, it is put into a low power state, extending the battery life. A sensor node can usually be in four different states: transmit, receive, idle, and sleep. The sleep state is significantly less energy consuming than the other states. Preserving network longevity is one of the main issues in sensor networks. The topology of the network is not known a priori because the nodes are randomly

scattered to a target area. Sensor networks are often dense networks. Not all the nodes are necessary to accomplish a specific request. One method to save energy is to put nodes to sleep in a manner that does not interfere with the functionality of the network. In a sensor network the lifetime of the network is more important than each sensor. Thus, the protocols developed for sensor networks consider the optimisation of network lifetime.

The topology of the network may be dynamic. Nodes may become temporary inactive to save their energy or they drain out of battery. At the same time, new nodes may be deployed in the same area. Energy is limited in the network. However, the nodes may have to repeatedly communicate with a base station on a hop-by-hop basis. To minimise the energy spent in the network, energy-preserving secure routing protocols (surveyed in the following subsection) have been developed. The communication patterns are concerned with balancing energy consumption and preserving network lifetime and purpose. Usually, the whole region needs to be covered by the nodes. The purpose of the network requires that the sensing coverage works for all localisations. At any location, the nodes should be able to send the collected data to the base station. Energy saving should not deteriorate the connectivity and the coverage of the network. An energy optimisation scheme should also maintain the initial coverage. Energy efficient schemes group sensors in different sets that are alternatively active (Cardei, 2005; Ramchurn, Jennings, Sierra, & Godo, 2004).

Another solution is to enforce clustering algorithms (Handy, 1995). An example of energy at the nodes level occurs with cluster-based sensors network topology. In this case, energy efficient routing protocols use hierarchical structures like clusters among the nodes forming the network. The nodes in the cluster only communicate with the cluster head. The cluster head is the only one to communicate with the other cluster heads and provides aggregation of data for the nodes forming the cluster.

The nodes that are not cluster head may receive the information later. The responsiveness of the node, concerning computation and communication, is also important. In addition to consuming more energy, the use of security mechanisms may also require more storage space, for example, for the keying material, and may slow down the processes due to the additional security steps, such as, encryption, decryption, and signatures.

Besides the above special assets, there are also more basic security assets, namely, the confidentiality/privacy, integrity, and availability properties of each node and their messages. When these basic assets are compromised, the other assets may be more easily compromised.

The list below summarises the different assets that we have discussed in this section:

- **Node-level assets:**
  - **Node mission lifetime:**
    - Node energy
      - Harvesting source
      - States and actions management
    - Node tamper-proof and tamper-evidence
  - Node localisation
  - Node mobility (in case of non-fixed settings)
  - Node computing performance
  - Node neighbours presence in interdependent settings
  - **Node communication:**
    - Ability
      - Reception
      - Transmission
      - Coverage range
    - Confidentiality
    - Integrity
    - Speed
- **Network of nodes-level assets:**
  - Network mission lifetime
  - Deployment of new nodes
  - Nodes participation and trustworthiness
  - Network connectivity, performance and coverage

The Routing Asset Case-Study

The nodes can use their wireless link to directly communicate with the other nodes in range. Sometimes the nodes can increase their transmission

energy to reach farther nodes. However, as said above, communication tasks use a lot of energy; for example, if we assumes Friss' (1946) free-space attenuation, the energy needed for wireless transmission over a distance *d* is proportional to *d square*. Thus, the nodes may save energy by using other closer nodes to forward their message to farther nodes. In addition, if the nodes cannot increase their transmission energy to reach a specific far-away node, the only remaining solution is to use intermediate nodes to forward the message. It is why routing algorithms have been researched. In this subsection, we survey the most well-known protocols that allow the nodes to exchange messages. We start by the MANET protocols and then the protocols said to be specific to sensor networks, which are explicitly energy-aware.

MANET Routing Protocols

Maltz (2001) depicts the history of MANETs. The first significant project towards MANETs is called the DARPA-sponsored military packet radio network (PRNET) in 1972. Now, MANETs seem to be used on battlefields. The goal of researchers, like Maltz, was to outperform the performance of the military protocols. They reached efficient and good performance for routing in MANETs with ad hoc on-demand distance vector routing (AODV) (Perkins & Royer, 1999) or dynamic source routing (DSR) (Maltz, 2001).

Both AODV and DSR are *reactive routing protocols* because they compute the route between two nodes only when the route is needed, that is, 'on demand.' In doing so, there are far fewer tasks to be carried out because all the routes do not have to be maintained all the time. It is very important from an energy point-of-view in mobile settings where the nodes come and go very quickly and where the routing information would need to be updated very often. However, neither AODV nor DSR integrate further specific mechanisms to minimise the energy consumption along the route.

Another limitation comes from the fact that Maltz and colleagues designed their protocols with the same assumption as for military MANETs. In military MANETs, it is often assumed that the deployed nodes are controlled; it is a controlled environment where it is understandably supposed that nodes are not free to do whatever they can do. In open MANETs, where any user's node can come and go depending on the user's will, the nodes might not follow the rules and they challenge the correct functioning of these routing protocols. Thus, the researchers had to revise their protocol approach (not to say restart from scratch) because all was working well under the assumption that the nodes do collaborate, but in open MANETs, where nodes are owned by free people, assuming that everyone collaborates is simply not realistic. In 2001, the conclusion was that security in MANETs is particularly difficult due to their specificities (Hubaux, Buttyán, & Capkun, 2001): vulnerability of channels and nodes (i.e., less physical security); resource-constrained nodes; high probability of absence of infrastructure; and dynamically changing topologies and high uncertainty. An interesting issue is the question of collaboration, which is vital for some MANETs to stay up: the nodes are neither dependent nor independent but interdependent. If too many nodes are too selfish, the overall availability is endangered (Miranda & Rodrigues, 2003).

Sensors Network Protocols

As mentioned above, in sensors networks, the deployed nodes are usually supposed to collaborate. However, due to their small size and the assumption that they can never be recharged, the MANET protocols are not sufficient to optimise the use of the energy of the nodes. This is why other researchers have researched new routing protocols with an emphasis on energy consumption optimisation. *Energy-aware routing protocols* explicitly take into account the energy consumption as a parameter. This subsection surveys seven of these new protocols that use one or several of these following energy saving basic techniques:

- Keeping short range transmissions
- Aggregating data
- Building efficient paths

- Switching between sleep/awake states
- Efficiently controlling multi-paths

During the set-up phase of the minimum cost forwarding algorithm (MCFA) (Ye, Chen, Liu, & Zhang, 2001), each node initiates its least cost to the sink estimated to be at an infinite distance. The sink broadcasts to its neighbours a setup message. Each of the neighbours computes and updates its least cost estimate to the sink and eventually broadcasts further to its own neighbours. When receiving a broadcast message, a node computes its new least-cost estimate. If it is lower than the current least cost estimate, the node updates it and broadcasts its new estimated least cost to its neighbours, and so on and so forth. In order to avoid collision as well as duplication of unnecessary message, that is, in order to optimise the flooding involved, MCFA introduces a back-off mechanism which is basically a timeout before propagating the updated values of the estimated least cost. During the propagation phase, when a node needs to send a message to the sink, it broadcasts to its neighbours. When a node receives a message, it checks if it is on the least cost path, and if so, propagates the message further. Otherwise it just drops the message.

Gradient-based routing (GBR) (Schurgers & Srivastava, 2001) is somehow similar to MCFA. It proposes to slide messages along a gradient towards the sink. GBR is a general scheme; it proposes a few gradients but it is open to other possible gradients. The gradient can be computed similarly as in MCFA, that is, using the back-off mechanism. If one wants to introduce the hop-count in the gradient, the hop-count is included in the gradient formula. MIX (Powell, Jarry, Leone, & Rolim, 2006) is a variant of GBR that allows the node to eject a message directly to the sink in case of high remaining energy on the current node compared to the energy remaining on its neighbours. In MIX, a sensor can choose to eject a message when all its short-range neighbours have lower energy than itself. To eject means that the sensor increases the power of transmission to be able to reach the base station in one transmission. As said above, the energy spent increases a lot, nonlinearly, with the distance. The ejection feature of MIX can be seen as a dynamic clustering technique: the ejecting nodes are cluster heads and the cluster members are nodes which propagate towards the ejectors. The cluster heads (and thus the clusters) are automatically updated by the distributed algorithm.

The low-energy adaptive clustering hierarchy (LEACH) (Handy, 1995) is a more well-known distributed randomised cluster formation algorithm. Many more complicated and optimised algorithms that exist in the literature have been inspired by LEACH. LEACH is based on partitioning the network into clusters. It features two distinct phases:

1. **Cluster formation:** Cluster heads are self-elected according to a very simple random rule: each node decides to become a cluster head with probability *p*, where *p* depends on a threshold value. This threshold function is dependent of parameters such as the remaining energy, the time elapsed since the network started, and the number of times it has been a cluster head before. Thus, energy balancing is possible through the fine-tuning of the parameters. Once self-elected, the cluster heads advertise themselves to noncluster heads by broadcasting an announcement message. Noncluster head nodes then decide to which cluster they will attach themselves. Basically, they attach themselves to the closest cluster head, although *closest* could have different meanings. Once the cluster head is aware of all of its cluster members, it computes a time division multiple access (TDMA) scheme and assigns a time slot to each of the members of the cluster. The cluster members are only allowed to transmit data to the cluster head during the time slot that they have been assigned to. Hence, no message collision occurs.
2. **Data propagation phase (once the clusters have been formed):** Data are sent by the cluster members directly to their cluster head. The cluster head then aggregates the data before sending them directly to the sink. Other protocols inspired by LEACH propose to run a more sophisticated algorithm than

direct transmission to the sink by using another routing protocol on a subgraph of the communication graph, sometimes called a 'backbone network,' where nodes are typically the cluster heads. The distributed cluster formation phase has to be rerun from time to time in order to avoid early energy depletion of cluster heads.

The directed diffusion (DD) (Intanagonwiwat, Govindan, Estrin, Heidemann, & Silva, 2003) protocol is also very famous but a bit more complicated than LEACH. It works roughly in the following way. The sink(s) sends *interests* (consisting of attribute value pairs) which are flooded across the network. The sources are being discovered as the nodes are capable of satisfying the interests. In a second stage, the gradients are being set (the exact way in which gradients are being set is application specific). Different gradients permit to build routes between the sources and the sink with different properties, for example, high robustness, low latency, low energy cost, and so forth. Information is propagated along the paths following the gradients. Energy can be further spared by carrying-out network data-aggregation as well as using caching techniques. DD seems to be very suitable for the so called *continuous monitoring* application domain (as opposed to *event driven* monitoring), because there is a cost in establishing the routes (or interests gradients, more precisely), and once they have been established they should be used for some time, that is, *continuously.*

In the sensor protocols for information via negotiation (SPIN) (Kulik, Heinzelman, & Balakrishnan, 2002), data are disseminated throughout the network, assuming that each sensor node is a potential sink. This is particularly efficient in the case of mobile networks. The protocol works in the following way. When a node detects an event, it sends an *ADV* message advertising the detected event. The nodes receiving the ADV decide if they are interested in the information, and if so, send a request (*REQ*) message, following which the actual data will be sent. The idea is to avoid unnecessary flooding of long data messages in the network when the information is redundant. The nodes decide to send REQ messages by analysing the ADV message which is assumed to contain the necessary information to take this decision. The actual encoding of the ADV message is application specific and not specified by the SPIN protocol. Variants of SPIN offer different optimisation for different contexts. For example, nodes can decide to stop participating when they believe that they do not have enough energy to complete all stages of the protocol.

The final protocol that we survey is probabilistic forwarding (PFR) (Chatzigiannakis, Dimitriou, Nikoletseas, & Spirakis, 2006). It uses the following approach which is common in routing protocols. In order to ensure robustness (due to link failure, message collision, etc.), data are propagated in a multipath way. However, the total number of paths has to be controlled. In PFR, it is assumed (although this assumption can be relaxed) that the angle of reception as well as the direction to the destination of a message can be computed. For example, this assumption is possible in a localised network. Using this information and by piggy-backing/adding $O(1)$ bits of information to the message, the nodes can probabilistically decide to forward or drop the message. The messages are propagated along a multipath beam whose width can be controlled by a parameter of the algorithm. The fact of being able to control the width of the beam enables the control of the energy cost overhead implied by multipath routing, and the fact of having a multipath beam ensures the robustness to link failure.

In the next subsection, we cover a specific form of failure, namely, failure due to malicious activities, also known as attacks.

Survey of the Attacks on the Nodes Assets

Above, we have surveyed the protocols that have been proposed for routing. These protocols are more or less energy-aware. However, most of the times these protocols assume that there is no attacker. As we are moving to a ubiquitous computing world, assuming that there is no attacker is unrealistic because the nodes are deployed in open environments where anybody can deploy nodes or try to tamper

with any nodes. We consider the cost of a physical attack as low because the nodes are assumed to not have significant tamper resistance due to the cost of such protection for devices that are supposed to be affordable for large scale deployment (Pirretti, Zhu, Narayanan, McDaniel, Kandemir, & Brooks, 2005). In a *node capture/tampering attack*, an adversary has physical access to the node. Current security solutions are evaluated by taking into account the resistance of the network to nodes capture, that is, the number of nodes needed to be captured in order to corrupt the entire network. Time is the factor used to evaluate the attacks that are in progress.

Another type of attack may especially target the energy asset. That form of attack is usually called the *energy starvation attack*. For example, Martin, Hsiao, Ha, and Krishnaswami, (2004) depict a denial-of-service attack targeting battery powered devices. Its purpose is to drain out the battery of the device, for example, by obliging the nodes to consume more energy than necessary. In the case of mobile computing devices, the attack leads to an inoperable device. It may only be temporary for a mobile device but it is usually not the case in sensors networks where the nodes cannot be recharged. In addition, the inoperability of several sensors can disrupt the functionality of an entire network region. An energy starvation attack may prevent the device from entering into its low power state, thus increasing the time while the device is active. This attack can be carried out in the case of the use of energy saving schemes. As said above, an energy saving scheme schedules for each node an awake/sleeping cycle. In a *sleep deprivation attack* a node is forced to remain in the awake state. We start by two types of energy starvation attacks. The first type is the sleep deprivation attack that targets the communication subsystem and prevents the sleep state. The second type called the barrage attack is enforced by demanding energy intensive operations. A node receives successive task requests.

Another possibility of increasing the energy consumption is to increase the energy needed for executing a task. The measure of the success of the attack may be the increase in overall energy consumption. The attack may be detected by the owner because the battery is expected to have a certain lifetime. Ultimately, the measure of this attack may be the report between the real and the expected lifetime of the battery. It has been reported that for mobile devices the report may be from one to two orders of magnitude (Pirretti et al., 2005). Martin et al. (2004) identify three types of sleep deprivation attacks on mobile devices. In a service request power attack, a device must repeatedly execute a network service on a remote entity. Even if the service is not available, the process of authentication consumes time and energy. Another type of power attack may be to request the devices to repeatedly execute an energy-hungry task. On mobile devices, power attacks may be detected by scanning software that compares the current energy consumption to normal energy consumption. On small sensors, it may be infeasible to run such scanning software. Other solutions analyse the energy consumption pattern because power attacks modify the energy consumption signature of the applications. Another solution may be to define and impose an energy limit for an application or a task.

The nodes executing important tasks, like cluster heads, are perfect targets to initiate stronger attacks over the other nodes in the cluster. These attacks are prevented by preventing the misbehaving nodes from becoming a cluster head. The solution evaluated by Pirretti et al. (2005) as the best to prevent this type of attack is a hash-based cluster head selection. The cluster head does not decide itself to be the next cluster head, but it is selected by random vote by the neighbours. This attack can be categorised as *topologically-inspired attack* (Seigneur, 2005), where the knowledge of the topology of the network of nodes is used to carry out more harmful attacks. This knowledge can be extracted by standard attacks that are also possible in our settings.

The messages sent by the nodes can be captured and read by attackers, which constitutes a confidentiality attack. A confidentiality attack may also be carried out to infer message provenance, route analysis, and activity monitoring. In some sensors network scenarios, it is crucial that the location of

the nodes that sensed the information is not known. For example, sensors network have been deployed to monitor the location of pandas in their natural habitat (Ozturk, Zhang, & Trappe, 2004). Due to the presence of hunters, source-location privacy is crucial. If we extend the scenario to the location of people, we can really talk of *source-location privacy attacks*. The network topology can be inferred from this information. More knowledge can help the attacker to carry out more harmful attacks targeting specific active/low-energy zones or traffic control. Among the other standard attacks, there are also the attacks that target the integrity of the messages as well as of the traffic or specific zones. The messages may be change replayed, delayed, or even destroyed.

As said above, the routing protocols work well when all nodes cooperate. However, in real settings, the cooperation assumption may not be valid. If the nodes are small, low-power devices, they are limited in energy and may be motivated to have a selfish, noncooperative behaviour when it comes to relaying the messages from other nodes. They can save power by not forwarding the messages received from the neighbours. Furthermore, selfishness is not the only misbehaviour that has to be addressed. An attacker can compromise nodes and then prevent packets to reach their destination. For example, in MIX, a few neighbour nodes may lie about their current energy level to avoid having to forward messages, or worse, they may not forward messages when asked to do so. In the latter case, these misbehaving nodes carry out an attack commonly called *sink hole attack* (Pirzada & McDonald, 2005). A sensor behaving like a sinkhole will drop any packet it receives. In a *worm hole attack* (Hu, Perrig, & Johnson, 2002), two colluding sensors create a tunnel between them. The first node may be situated in the proximity of the base station and replays the messages received by the second one. The tunnel is a fast path and will encourage the nodes to use it for routing. This attack is hard to detect because the authenticity and confidentiality security requirements are maintained. Once the packets are routed through the wormhole, *denial-of-service attacks* can be enforced. Packets will be forwarded selectively or they will be not forwarded at all. In a *Sybil attack* (Douceur, 2002), a node uses multiple identities without revealing that it owns these different identities. If some mechanisms in the network use the majority of votes in their decision making, a node with many identities can cheat during the voting process by using more than one vote. For a routing protocol that use several paths to the destination, a Sybil attack can advertise one path as several ones. Additionally, a Sybil attack can be correlated with sink hole or worm hole attacks.

PROTECTION MECHANISMS

Different protection mechanisms have been proposed to increase the survivability of the nodes and protect their assets. For example, a few of the surveyed above routing protocols have recently been patched with security mechanisms: secureSPIN (Xiao, Wei, & Zhou, 2006) adds cryptographic functions to SPIN that do not require too much memory and processing power; and secure directed diffusion (SDD) (Wang, Yang, & Chen, 2005) uses an efficient one-way chain rather than asymmetric cryptography, which is too complex for the resource-constrained nodes, to increase the security of the protocol. Indeed, the cost of the protection mechanisms has to really be taken into account due to the resource-constraints of the nodes. Cryptographic solutions may be used for confidentiality and integrity of data but they may be too heavy in some settings. Any protection mechanism needs to be analysed with regard to its computation cost, its memory cost, its communication cost, and its energy cost (Hwang et al., 2004). In the next subsections, we detail two fast-evolving protection mechanisms: cryptographic key deployment and management among the nodes, and computational trust management.

Key Deployment and Management

A first line of defence is the use of cryptography to encrypt the communication between the nodes. However, this requires the distribution/deployment of secrets in the nodes to allow them to encrypt the

communication with this secret. The distribution of keys is usually followed by a shared key discovery phase and a path key establishment phase. Other elements that need to be considered are key revocation, rekeying, and addition of nodes. Two neighbour nodes can communicate only if they share the same key. Network resilience is defined as the number of captured nodes before an attacker is able to control the network. Network connectivity is defined as the probability that two nodes can communicate. Rekeying overhead is defined as the network traffic needed to establish a new key. Both network resilience to node capture and pair-wise connectivity depends on the size of keying material stored on the nodes. While public key cryptography is not feasible due to limited computational resources, the distribution of secret keys to each sensor is assumed to be feasible in the literature. As we underlined above, the nodes are low cost devices without strong tamper proof hardware. Thus, a captured node will, at some stage, permit access to its cryptographic material. Key management schemes (Chan, Perrig, & Song, 2003; Mohammed & Mohamed, 2005) try to increase network resilience to node capture while maintaining the performance goals and minimising the resulting cost of lower network connectivity due to sensors who do not share similar secret keys. There is a trade-off between the energy spent, the cost of used memory for protection, and the security level reached (Hwang et al., 2004).

Static keying means that the nodes have been allocated keys off-line before deployment, that is, predeployment. The existing solutions assign keys either randomly or based on deployment information, for example, the predicted neighbourhood of the nodes. A basic scheme is to generate p keys off-line and the nodes are allocated k keys randomly among these p keys. After deployment, a node broadcasts a set of identifiers of its known keys and can communicate with the nodes that have at least one common key. The advantage of static keying is no communication overhead after the deployment. The easiest way to secure a network is to give a unique key at predeployment time. However, in this case, if only one node is compromised the whole network is compromised and it seems viable to extract the key from one node as they are cheap and not so well protected (at least in nonmilitary application scenarios). The second approach is to have pairwise keys for all sensors on each sensor, which is impractical due to the memory constraints of the sensors. Saurabh and Mani (2004) argue that previous approaches relying on keying management and cryptographic means are not suitable for small nodes, such as sensors, due to their resource constraints or the fact that it is easy to recover their cryptographic material because they are cheap and not fully tamper-proof. For n nodes deployed in the network, each node would have to store n-1 keys. Even if the keys are small (e.g, 64 bits), for a network of tens of thousands of nodes the storage space required for the keys is impractical. It is worth noting that only a small fraction of the keys may be used in fixed standard sensors networks because the density of the network may be low and a sensor may only be able to communicate with few neighbouring nodes with direct communication. Eschenauer and Gligor (2002) mitigate the memory constraints problem whilst keeping the key resilience level at a target threshold level. If we consider N the number of nodes in the network and p the probability that two nodes share a common key, then each node will store a set of Np keys, called a *key ring.* The keys are selected from a larger *key pool*. Each node stores a set of keys and an identifier for each key. A *shared key discovery phase* between the neighbours is necessary after the deployment. Each node broadcasts the identifiers of the keys in its key ring. If the nodes share a common key, there is a link between them. If a common key between two nodes does not exist, then a *path key establishment* procedure takes place. An alternative is to use location information to improve connectivity. Polynomial-based key predistribution schemes (Chan et al., 2003) use a random symmetric t-degree polynomial P. A *polynomial share* is defined as a partially evaluated polynomial: $P(i,y)$ or $P(y,i)$. Based on the polynomial share, each node can compute a common key: $f(i,j)$. The scheme is resistant to t collusions.

Dynamic keying means that the keys can be (re)generated after deployment. New keys are cre-

ated in order to prevent a potential attacker from using the keying information obtained by node capture. It creates more communication overhead but stronger resilience to node capture. Dynamic key management schemes are based on the exclusion basis systems (EBS) (Mohammed & Mohamed, 2005). There is an initial pool of $k+m$ keys. Each node stores k keys. Rekeying is carried out from time to time because there is the assumption that some nodes are captured from time to time. The m keys that are unknown to the captured nodes are used to encrypt replacement keys that are distributed to the safe nodes. However, since m is usually chosen quite small to limit the number of messages needed for rekeying, a few nodes may be enough to collude and unveil the keys of the whole network. To mitigate this issue, Mohammed and Mohamed (2005) propose a variant based on key polynomials instead of basic keys. Each node stores k polynomials of t-degree out of a $k+m$ pool of polynomials. In order to obtain a key, $t+1$ shares of each polynomial are needed. Another approach to mitigate the attacks of colluding nodes may be to evaluate the trust that can be placed in the involved nodes.

Computational Trust Management

In the human world, trust exists between two interacting entities and is very useful when there is uncertainty in result of the interaction. The requested entity uses the level of trust in the requesting entity as a mean to cope with uncertainty and to engage in an action with potential benefits in spite of the risk of a harmful outcome. In our settings, the nodes may be interdependent, for example, to reach far away nodes via routing and forwarding between intermediate nodes. We have seen above that it is an asset for the nodes to have trustworthy neighbours and *computational trust* is a means to compute trust in them. There are many definitions of the human notion trust in a wide range of domains with different approaches and methodologies (McKnight & Chervany, 2000), such as sociology, psychology, economics, pedagogy, and so forth. Romano's (2003) recent definition tries to encompass the previous work in all these domains.

Trust is a subjective assessment of another's influence in terms of the extent of one's perceptions about the quality and significance of another's impact over one's outcomes in a given situation, such that one's expectation of, openness to, and inclination toward such influence provide a sense of control over the potential outcomes of the situation.

A computed trust value in an entity may be seen as the digital representation of the trustworthiness or level of trust in the entity under consideration; a nonenforceable estimate of the entity's future behaviour in a given context based on evidence (Trustcomp, n.d.). A computational model of trust based on social research was first proposed by Marsh (1994). Trust in a given situation is called the *trust context.* Each trust context is assigned an importance value in the range [0,1] and utility value in the range [-1,1]. Any trust value is in the range [-1,1). Risk is used in a threshold for trusting decision making. Evidence encompasses outcome observations, recommendations, and reputation. The propagation of trust in peer-to-peer network has been studied by Despotovic and Aberer (2004) who introduce a more efficient algorithm to propagate trust and recommendations in terms of computational and communication overhead. Such overhead is especially important in networks of nodes as any communication overhead requires more energy spending.

A high level view of a trust engine is depicted in Figure 1. The decision-making component can be called whenever a trusting decision has to be made. Most related work has focused on trust decision making when a requested entity has to decide what action should be taken due to a request made by another entity, the requesting entity. It is the reason that a specific module called entity recognition (ER) (Seigneur, 2005) is represented to recognise any entities and to deal with the requests from virtual identities. In our network of nodes settings, when keying material is used, the nodes may be recognised via the secret keys that they own and use.

The decision making of the trust engine uses two subcomponents:

1. A trust module that can dynamically assess the trustworthiness of the requesting entity based on the trust evidence of any type stored in the evidence store.
2. A risk engine that can dynamically evaluate the risk involved in the interaction, again based on the available evidence in the evidence store.

A common decision-making policy is to choose (or suggest to the user) the action that would maintain the appropriate cost/benefit. For example, in the sensor network application domain, we have to balance ejecting a message or forwarding it based on how much energy has to be spent and risk of failure in each case to successfully reach the base station or sink. In the background, the evidence manager component is in charge of gathering evidence such as recommendations, comparisons between expected outcomes of the chosen actions and real outcomes, and so forth. These pieces of evidence are used to update risk and trust levels. Thus, trust and risk follow a managed lifecycle.

Although 'subjective logic' (Jøsang, 2001) does not use the notion of risk, it can be considered as a trust engine that integrates the element of ignorance and uncertainty, which cannot be reflected by mere probabilities but is part of the human aspect of trust. In order to represent imperfect knowledge, an opinion is considered to be a triplet whose elements are belief (*b*), disbelief (*d*), and uncertainty (*u*), such that:

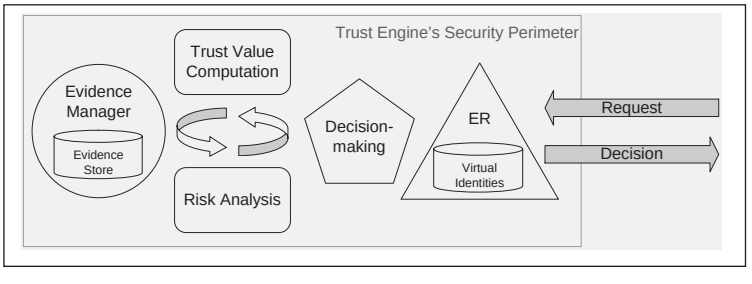
$b + d + u = 1 \qquad \{b, d, u\} \in [0,1]^3$

The relation with trust evidence comes from the fact that an opinion about a binary event can be based on statistical evidence. Information on posterior probabilities of binary events are converted in the *b, d,* and *u* elements in a value in the range [0,1]. The trust value (*w*) in the virtual identity (*S*) of the virtual identity (*T*) concerning the trust context *p* is:

$$w^{T}_{p(S)} = \{b, d, u\}$$

The subjective logic provides more than 10 operators to combine opinions. For example, the recommendation (⊗) operator corresponds to use the recommending trustworthiness (*RT*) to adjust a recommended opinion. Jøsang's approach can be used in many applications since the trust context is open. In the case of our networks of nodes, we can apply this kind of triple and statistical evidence count to compute the node trust value. For example, in case of a sink base station and a network of nodes, the messages sent by a node may be acknowledged by the base station by sending an acknowledgement message with strong energy transmission. Depending on which neighbour node was used to forward the message, the sending node can count how many times the sent messages were acknowledged via this neighbour node. Each neighbour node is given a triple (*b, d, u*) as its trust value. If a message is acknowledged, *b* is increased by one. If after a timeout, the message has still not been acknowledged, *d* is updated by one. From the sending time of the message to the acknowledgement or the timeout, *u* is increased by 1 (and then decreased by 1). Concerning the memory/protection cost trade-off (Hwang et al., 2004), it seems to be a reasonable assumption be-

Figure 1. High-level view of a trust engine



cause there are usually few neighbours and there is enough memory space for a few triples. However, each node has to maintain active the radio link, in the so-called promiscuous mode, in order to listen to the activity of the neighbours. Since sensors are low energy devices, the energy consumption due to the listening state represents a major drawback of any trust system.

Several other mechanisms have been proposed to make decisions about whether to cooperate or not with their peer nodes based on their previous behaviour. The information used to build the reputation value of the neighbours is collected mainly by direct interactions and following observations. Although it is accurate, it requires some time before enough evidence has been collected. In a scenario consisting of static nodes such as deployed sensors, there is more time to build trust with the neighbour sensors because they do not move. In this case, one may consider using a temporary ramp-up counter of 10 messages in the trust metrics to be sure of the behaviour of the node. If recommendations are used, the reputation of the nodes that provide the recommendations has to be taken into account. In this latter case, it may create a vulnerability to false report attacks. We survey below the other trust models that have been applied to the application domain of resource-constraint nodes and sensors networks.

Michiardi and Molva's (2002) core trust model builds the reputation of a sensor as a value that is increased on positive interactions and decreased otherwise. It takes also into account positive ratings from the neighbours. If the aggregated value of the reputation is positive, the sensor cooperates, otherwise it refuses cooperation. Buchegger and Le Boudec's (2004) confidant trust model considers only negative ratings from the neighbours and monitors the communication to detect the nodes that do not forward the messages. In order to compute a reputation value, different weights are assigned to personal observations and reported reputations. Concerning the memory/protection cost trade-off (Hwang et al., 2004), it seems feasible because they only forward second-hand information/recommendations, called alarms, to a limited number of nodes, called friends, maintained in a simple table. However, the monitor module of confidant still requires the consumption of a non-negligible amount of energy for resource-constrained nodes. Saurabh and Mani's (2004) trust model uses only positive ratings and models the reputation value as a probabilistic distribution by the means of a beta distribution model. A sensor will cooperate with the neighbours that have a reputation value higher than a threshold. Twigg's (2003) trust model focuses on the MANET DSR protocol and on the relation between trust value communication and energy cost. He assumes Friss' free-space attenuation to compute the risk and cost of ejecting to more or less far nodes. He proposes to consider aggregate properties including retransmissions and calculate the probability of successful transmission before a certain time. Pirzada and McDonald (2005) introduce the use of computational trust based on direct observations to mitigate both sinkhole and wormhole attacks. However, their work is also limited to the MANET DSR protocol. They cover two trust contexts: trust packet precision (TPP) for wormhole and trust packet acknowledgment (TPA) for sinkhole. They combine the two trust contexts. If the sensor is suspected to be a wormhole, the combined trust value T is 0. Otherwise TPP is equal to 1. TPA is a counter that is incremented each time a node is used to forward a packet and an acknowledgement has been received before a timeout; it is decreased otherwise. The inverse of the combined trust value simply replaces the default cost of 1 in the LINK CACHE of the standard DSR protocol. If it is a wormhole the cost is set to infinity.

FUTURE TRENDS

In the future, the importance of the energy asset of the nodes may decrease. For example, a new energy solution may come from new contact-less, distant energy transfer means to recharge nodes, such as via inductive coupling. In addition, although current energy harvesting mechanisms have performance and size limitations, the advances in nanotechnologies may allow even small nodes to effectively harvest energy after deployment. For

example, solar cells in new nanomaterial are much more flexible than before. In this case, the attacks may be turned towards the external harvested energy sources.

The advances in nanotechnologies may also mean that even smaller nodes are possible. In this case, it is likely that current cryptographic mechanisms will have to be scaled down. Routing and communication between these nanoscale nodes may also change dramatically. Quantum computing may introduce even further probabilistic mechanisms with less determinism at the node level than at the nodes as a whole level. In this case, decision-based under uncertainty may still benefit from the use of computational trust.

CONCLUSION

Due to the resource-constraints of the nodes involved in mobile ad hoc or sensors networks settings, new security mechanisms are needed to guarantee the survivability of these networks of nodes. However, these new security mechanisms have a strong constraint with regard to their resource consumption. Computational trust management is one of these new schemes that are proposed because the nodes are interdependent and need to collaborate to achieve more that what they can achieve alone. There are still limitations though: both the listening mode and the communication overhead are costly in terms of energy. The cryptographic tasks involved in key management consume less energy but rekeying still necessitates extra communication. There is still some work ahead to fine-tune and combine these new security mechanisms for optimal survivability, being survivability at the node level or at the network of nodes level.

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KEY TERMS

Node: A node may go from the tiny fixed deployed sensor to the mobile unplugged mobile device.

Node(s) Survivability: Emphasises that the scope of the nodes mission may span more than one node. The survivability of the node itself may be more important than the survivability of the other nodes or the mission may be that the majority of the nodes survive at the expense of the survival of one specific node.

Reactive Routing Protocols: Compute the route between two nodes only when the route is needed, that is, 'on demand.'

Energy-aware Routing Protocols: Explicitly take into account the energy consumption as a parameter.

To Eject: Means that the sensor increases the power of transmission to be able to reach the base station in one transmission.

Static Keying: Means that the nodes have been allocated keys off-line before deployment, that is, predeployment.

Dynamic Keying: Means that the keys can be (re)generated after-deployment.

Network Resilience: The number of captured nodes before an attacker is able to control the network.

Network Connectivity: The probability that two nodes can communicate.

Rekeying Overhead: The network traffic needed to establish a new key.

Trust: Trust 'is a subjective assessment of another's influence in terms of the extent of one's perceptions about the quality and significance of another's impact over one's outcomes in a given situation, such that one's expectation of, openness to, and inclination toward such influence provide a sense of control over the potential outcomes of the situation' (Romano, 2003).

Computed Trust Value: A nonenforceable estimate of the entity's future behaviour in a given context based on evidence ("Trustcomp," n.d.).

Chapter XL
Fault Tolerant Topology Design for Ad Hoc and Sensor Networks

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ABSTRACT

Fault tolerance is one of the premier system design desiderata in wireless ad hoc and sensor networks. It is crucial to have a certain level of fault tolerance in most of ad hoc and sensor applications, especially for those used in surveillance, security, and disaster relief. In addition, several network security schemes require the underlying topology provide fault tolerance. In this chapter, we will review various fault tolerant techniques used in topology design for ad hoc and sensor networks, including those for power control, topology control, and sensor coverage.

INTRODUCTION

With great potentials in a large number of application fields, ad hoc and sensor networks have been undergoing a revolution that promises a significant impact on society. Unlike traditional fixed infrastructure networks, there are no centralized controls over wireless *ad hoc* networks, which consist of a collection of devices equipped with wireless communication and networking capability. Any communication and network service in ad hoc networks is done in a self-organized and decentralized manner. Usually connections are multihop routed via intermediate nodes to enable communication between nodes without a direct link. A wireless sensor network is a network of small, wirelessly communicating nodes where each node is equipped with computation, communication, and sensing devices. These nodes usually form a self-organized ad hoc network, observe the physical space around them, and measure some physical signals or detect various phenomena of interest. Ad hoc and sensor networks are widely deployed for environment monitoring, biomedical observation, surveillance, security, disaster relief, and so on.

Ad hoc and sensor networks trigger many challenging research problems, as they intrinsically have many special characteristics and unavoidable limitations, compared with other wired or wireless networks. An important requirement of ad hoc and sensor networks is that they should be self-organizing, that is, transmission ranges and data paths are dynamically restructured with changing topology. Energy conservation and network performance are probably the most critical issues in ad hoc and sensor networks, since wireless devices (such as tiny sensor nodes in sensor networks) are usually powered by batteries only and have limited computing capability and memory. Topology control and power control are two primary techniques with respect to energy-efficiency in ad hoc and sensor networks.

The topology control technique is to let each wireless device locally select certain neighbors for communication, while maintaining a topology that can support energy efficient routing and improve the overall network performance. Unlike traditional wired networks and cellular wireless networks, mobile devices are often moving during the communication, which could change the network topology in some extent. Hence it is more challenging to design a topology control algorithm for ad hoc and sensor networks. The power control technique is to control the network topology by adjusting the wireless device's transmission range. Reducing the transmission range can save the power consumption at each node and reduce the signal interference among neighbors, but it may hurt the connectivity of the induced topology. Power control tries to minimize the power consumption used by all nodes while maintaining a topology that is connected and has certain desired properties such as fault tolerance.

Although fault tolerance has been studied for several decades in computer and VLSI systems, limited resources on small devices, lack of centralized control, and high mobility make fault-tolerance much harder to achieve in ad hoc and sensor networks. One key characteristic of such networks is that node and link failure is an event of non-negligibility, in some cases even as a regular or common event. This is particularly the case in sensor networks where the equipment is restricted to a minimum due to limitations in cost and weight. First of all, battery driven sensor nodes may stop working because they run out of energy supply. Second, the shared wireless medium is inherently less stable than wired media. This situation results in more packet losses and lower throughput. Third, sensor networks often operate in potentially hostile or at least harsh and unconditioned environments. Tiny sensor devices with limited security techniques are usually vulnerable from various attacks. Another aspect that has an influence on the required degree of redundancy and fault-tolerance is mobility, which is a key issue in ad hoc networks. Therefore, reliability and fault-tolerance are emerging as premier and crucial system design desiderata in ad hoc and sensor networks. In addition, fault-tolerance design is also one of basic components in ad hoc and sensor network security.

Fault tolerance strongly depends on the network connectivity. To make fault tolerance possible, first of all, the underlying network topology must be k-connected for some $k > 1$, that is, given any pair of wireless devices, at least k disjoint paths are needed to connect them. With k-connectivity, the network can survive k-1 node/link failures. Traditional topology control or power control solutions cannot cope with those fault-tolerance requirements, since fault-tolerance is usually sacrificed for power efficiency. In order to be power efficient, topology control and power control algorithms try to reduce the number of links and thereby reduce the redundancy available for tolerating node and link failures. On the other hand, to achieve fault-tolerance, existing algorithms usually sacrifice power efficiency concern. Thus, topology design for ad hoc and sensor networks needs to consider both power efficiency and fault-tolerance.

This chapter is focused on fault tolerant topology design for ad hoc and sensor networks. In the second section, fault tolerant techniques used in power control protocols (such as power assignment and critical transmission range) are reviewed. In the third section, we survey fault tolerant design in topology control, that is, how to design fault tolerant geometric or hierarchical structures. In the

fourth section, fault tolerant coverage and protection in sensor networks are discussed. There is a conclusion in the fifth section, while the chapter ends with references and key definitions.

FAULT TOLERANT DESIGN IN POWER CONTROL

Fault tolerant design in power control studies how to set the transmission range for each node in a network such that the induced topology is *k*-connected, that is, the network can survive under *k*-1 failures. Obviously, by setting the transmission range sufficiently larger, the induced network topology will be *k*-connected without doubt. However, as power is a scarce resource in ad hoc and networks, it is important to save the power consumption without losing the network connectivity. Thus, the question is how to find the minimum transmission range such that the induced topology is multiply connected. There are two sets of research in this direction: *critical transmission range* for random networks and *minimum power assignment optimization* for static networks.

Given n static wireless nodes V, each with transmission range r_n, the wireless network can be modeled by graph $G(V,r_n)$ in which two nodes are connected if their Euclidean distance is no more than r_n. The minimum range r_n used by all wireless nodes such that the induced network topology has certain property (such as connectivity) is called the *critical transmission range* (CTR). The CTR for connectivity has been studied in the literature (Gupta & Kumar, 1998; Penrose, 1997; Ramanathan & Rosales-Hain, 2000; Sanchez, Manzoni, & Haas, 1999). Characterizing the CTR for connectivity (or *k*-connectivity) helps the system designer to answer fundamental questions, such as: (1) given a number of nodes *n* to be deployed in a region, what is the minimum value of transmission range that ensures network connectivity (or *k*-connectivity)?; or (2) given transmission range of certain technology, how many nodes need to be distributed over a given region to ensure network connectivity (or *k*-connectivity)?

Recently, applying stochastic geometry, Penrose (1999), Bettstetter (2002), Li, Wang, Wan, and Yi (2003), and Wan and Yi (2004) studied CTR to achieve the *k*-connectivity with certain probability for a network when wireless nodes are uniformly and randomly distributed over a two-dimensional region. Penrose (1999) shows that with high probability the network becomes *k*-connected when the minimum node degree in the communication graph becomes *k*. In other words, the characterization of the CTR for *k*-connectivity can be derived by analyzing the probability of the relatively simpler event that every node in the network has a degree at least *k*. Based on results from Penrose, Li et al. (2003) first derives the upper bound and the lower bound of the CTR for *k*-connectivity in a two-dimensional network. They proved that, given *n* wireless nodes which are randomly distributed in a unit square, if the transmission range r_n of wireless devices satisfies, $n\pi \cdot r_n^2 \geq \ln n + (2k-3)\ln\ln n - 2\ln(k-1)$ $!+ \alpha + 2\ln(8(k-1)/(2^{k-1}\sqrt{\pi}))$ then $G(V,r_n)$ is *k*-connected with probability at least $e^{-e^{-\alpha}}$ as n goes to infinity. Here α is any real number. Wan and Yi (2004) close the gap between the upper bound and the lower bound by giving an exact formula for the probability of *k*-connectivity when n goes to infinity. They show the CTR for *k*-connectivity: $r_n = \sqrt{(\log n + (2k-3)\log\log n + f(n))/\pi n}$ where $f(n)$ is an arbitrary function such that $\lim_{n\to\infty} f(n) = +\infty$. Bettstetter (2002) also investigated the minimum node degree and *k*-connectivity and constructed various simulations to verify his analytical expressions. However his theoretical result does not consider the boundary effects (assume the network is distributed in a very large area), which is impossible in real networks. Even though the theoretical results of the CTR for *k*-connectivity has been derived, the theoretical bounds only hold when n goes to infinity. How to set the transmission range in a real network where n is a small pratical integer is studied by Li et al. (2003) by conducting simulations. Another related work is about the CTR for connectivity with Bernoulli nodes. So far we assume that all nodes will always function properly, however, in certain scenarios, nodes may be fault (or put into sleep) with a certain

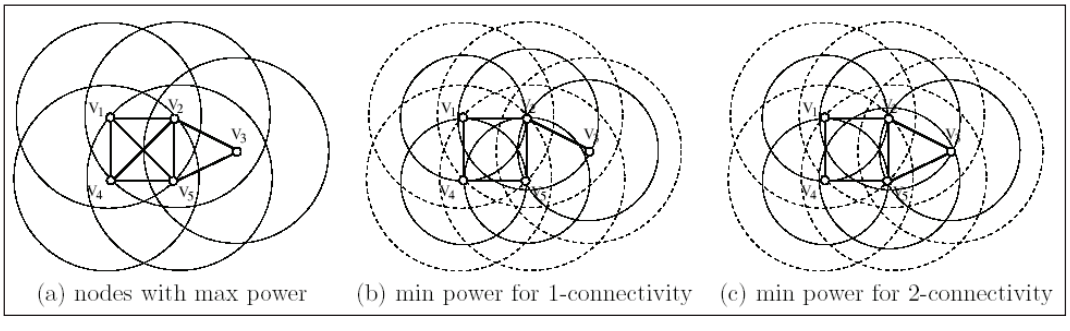
probability $p > 0$. Wan and Yi (2005) model this scenario using Bernoulli nodes and studied the CTR for connectivity with Bernoulli nodes.

All analytical results on CTR assume wireless nodes are randomly distributed and the transmission range of every node is equal. These assumptions are not always true for ad hoc and sensor networks in practice. Another power control technique is to allow each wireless device to adjust its transmission power according to its neighbors' positions. A natural question is then, given a static network, how to assign the transmission power for each node such that the network is *k*-connected with optimization criteria minimizing the total (or maximum) transmission power assigned. This kind of optimization questions is called *minimum power assignment optimization*. See Figure 1 for illustrations of minimum total power assignment for *k*-connectivity ($k = 1$ or 2).

The *minimum maximum power assignment problem* can be solved in polynomial time by using a simple binary-search-based approach (Lloyd, Liu, Marathe, Ramanathan, & Ravi, 2002). The *minimum total power assignment for connectivity problem* was first studied and proved to be NP-hard by Chen and Huang (1989), in which the induced communication graph is strongly connected while the total power assignment is minimized. Recently, this problem has been heavily studied and many approximation algorithms have been proposed when the network is modeled using symmetric or asymmetric links (Althaus, Calinescu, Mandoiu, Prasad, Tchervenski, & Zelikovsly, 2003; Calinescu, Kapoor, Olshevsky, & Zelikovsky, 2003; Clementi, Penna, & Silvestri, 2000; Clementi, Huiban, Penna, Rossi, & Verhoeven, 2002; Kirousis, Kranakis, Krizanc, & Pelc, 2000; Ramanathan & Rosales-Hain, 2000). Along this line, Calinescu and Wan (2006), Cheriyan, Vempala, and Vetta (2002), and Hajiaghayi, Immorlica, and Mirrokni (2003) consider the minimum total power assignment while the resulting network is *k*-connected (or (*k*-1) fault tolerant). This problem has been shown to be NP-hard too. Many of the best-known approximation algorithms (e.g., Cheriyan et al., 2002) are based on linear programming (LP) approaches. However, Haijaghayi et al. (2003) show that for the minimum total power assignment for *k*-connectivity problem, the natural integer LP formulation has an integrality gap of $\Omega(n/k)$, implying that there is no approximation algorithm based on LP with an approximation factor better than $\Omega(n/k)$.

Some heursitics (Bahramgiri, Hajiaghayi, & Mirrokni, 2002; Ramanathan & Rosales-Hain, 2000) are proposed as well. Bahramgiri et al. (2002) show that the cone-based topology control (CBTC) algorithm by Wattenhofer, Li, Bahl, and Wang (2001) and Li, Halpern, Bahl, Wang, and Wattenhofer (2001) can be extended to slove the *k*-fault tolerance. Haijaghayi et al. (2003) also constructed examples which demonstrate that the approximation factor for CBTC algorithm is at least $\Omega(n/k)$. Recently, Lloyd et al. (2002) presented a centralized $8(1\text{-}1/n)$-approximation for the minimum total power assignment for 2-connectivity problem. Calinescu and Wan (2006) further show that their algorithm could achieve $2k$-approximation ratio for the minimum total power

Figure 1. Illustrations of power control: minimum total power assignment for connectivity



assignment for *k*-connectivity problem. Haijaghayi et al. (2003) present algorithms minimizing power while maintaining *k*-connectivity with guarantee. Their first algorithm gives an $O(k\alpha)$-approximation where α is the best approximation factor for the related problem in wired networks (the best α so far is in $O(\log k)$ by Cheriyan et al., 2002)). The second algorithm is based on an approximation algorithm introduced by Kortsarz and Nutov (1994). It is more complicated and can achieve $O(k)$ approximation for general graphs. Their first two algorithms are centralized algorithms. Then they present two distributed approximation algorithms for the cases 2- and 3-connectivity in geometric graphs with constant approximation ratios. Both these algorithms use the distributed minimum spanning tree algorithm.

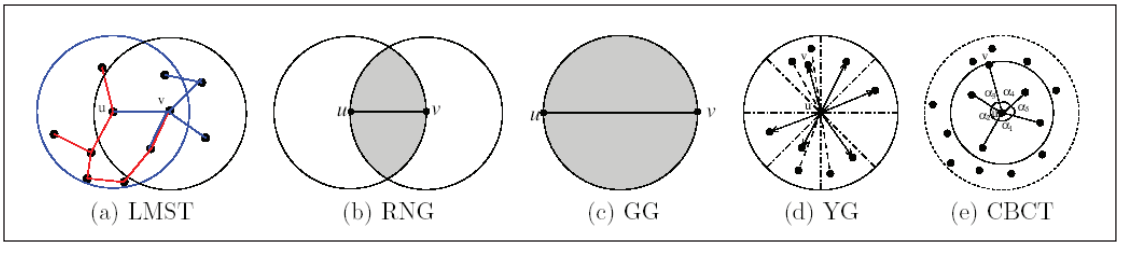
FAULT TOLERANT DESIGN IN TOPOLOGY CONTROL

Topolgoy control algorithms have been proposed to maintain network connectivity while improving energy efficiency and increasing network capacity by solely keeping selected links. However, by reducing the number of links in the network, topology control actually decreases the degree of routing redundancy. As a result, the induced topology is more susceptible to node failures or departures. Thus, in this section we review the fault tolerant design which enforces *k*-connectivity in the topology control process. Usually, there are two sets of solutions for topology control: geometric topology (flat structure) and virtual backbone (hierarchical structure).

Geometric topology control algorithms assume each node knows the position information of itself and its neighbors and all nodes have the same transmission range. Using this geometric information, each node makes a local decision to keep some links and remove other links. Well-known geometric topologies used in ad hoc networks include local minimum spanning tree (LMST) (Li, Hou, & Sha, 2003), relative neighborhood graph (RNG) (Bose, Morin, Stojmenovic, & Urrutia, 2001; Seddigh, Gonzalez, & Stojmenovic, 2002), Gabriel graph (GG) (Bose et al., 2001; Karp & Kung, 2000), Yao graph (YG) (Li, Wan, & Wang, 2001; Li, Wan, Wang, & Frieder, 2002) and CBTC (L. Li et al., 2001; Wattenhofer et al., 2001). See Figure 2 for illustrations of their definitions. All of these topologies do guarantee the connectivity but not fault tolerance. Therefore, variations of these topologies have been proposed to improve the fault tolerance, that is, preserving *k*-connectivity.

Li and Hou (2004) present a variation of LMST algorithm to construct a k-connected topology, called fault-tolerant local spanning subgraph ($FLSS_k$). Similarly to LMST, algorithm to build $FLSS_k$ is composed of three phases: information exchange, topology construction, and determination of transmit power. The main difference between LMST and $FLSS_k$ is in the topology construction phase: instead of building a local MST on its neighbor (such as the two local trees for *u* and *v* in Figure 2[a]), a node builds a spanning subgraph to preserve *k*-connectivity using a simple greedy algorithm. Li and Hou prove that $FLSS_k$ guarantees the *k*-connectivity and maintains bidirectionality for all the links in the topology while reducing the power consumption.

Figure 2. Illustrations of the definitions of different topologies



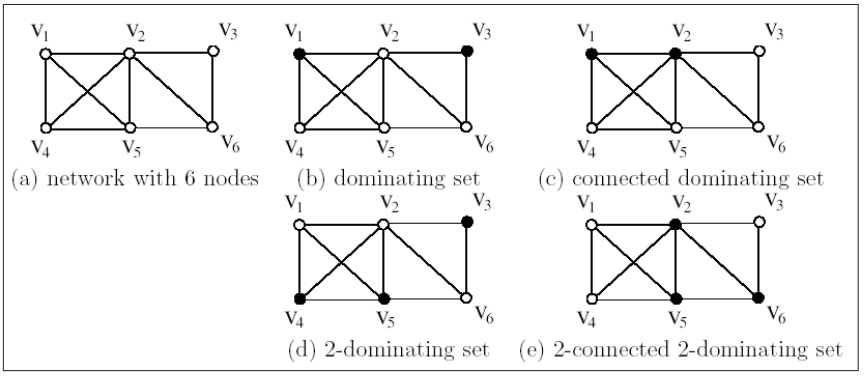
Zhou, Das, and Gupta (2005) generalize the RNG structure to *k*-RNG structure to preserve the *k*-connectivity for sensor networks. In RNG, a link *uv* exists if and only if there is no other node *w* with edges *uw* and *wv* satisfying $||uw||<||uv||$ and $||wv||<||uv||$ simultaneously. Here $||.||$ is the Euclidean distance. See Figure 2(b). In *k*-RNG, an edge exists between *u* and *v* if and only if there are at most (*k*-1) nodes *w* that satisfy $||uw||<||uv||$ and $||wv||<||uv||$. Obviously, similar to RNG, *k*-RNG can be constructed locally. Zhou et al. proved that *k*-RNG is *k*-connected if the original communication graph is *k*-connected. Notice that it is also easy to show we can use the same idea to generalize GG structure to *k*-GG while preserving the *k*-connectivity. There is an edge *uv* in *k*-GG if and only if there are at most (*k*-1) nodes inside the disk with *uv* as the diameter. See Figure 2(c). The nice property of GG and *k*-GG is that their power spanning ratios are equal to one (X.-Y. Li et al., 2001, 2002). In other words, GG/*k*-GG can keep all links on least power consumption paths in the original communication graph. Notice that LMST/$FLSS_k$ and RNG/*k*-RNG do not have this property.

X.-Y. Li et al. (2003) modifiy the Yao structure as follows such that the structure is *k*-connected. Each node *u* defines any *p* equally-separated rays originated at *u*, where $p > 6$. These rays define *p* cones inside the transmission range. Figure 2(d) shows an example with $p = 8$ cones. In each cone, *u* chooses the *k* closest nodes in that cone, if there is any, and adds directed links from *u* to these nodes. Ties are broken arbitrarily. X.-Y. Li et al. (2003) proved that the modified Yao structure ($YG_{p,k}$) can preserve the *k*-connectivity. In addition, $YG_{p,k}$ is a length/power spanner with bounded node degree even when (*k*-1) nodes fault. Here a length/power spanner has constant length spanning ratio and power spanning ratio, which indicates the topology is power efficient for unicast routing.

Bahramgiri et al. (2002) also discuss how to generalize the CBTC algorithm to ensure *k*-connectivity. Basically, for each node, it enlarges the transmission range until it reaches its maximum power or the maximum angle between two consecutive neighbors of the induced topology is at most $2\pi/(3k)$. See Figure 2(e). Finally, it eliminates one-directional edges and keeps bidirectional edges. Bahramgiri et al. (2002) proved the resulted topology is *k*-connected if the original graph is *k*-connected. We can also prove the topology is a length spanner even with (*k*-1) nodes faults. However, unlike $YG_{p,k}$, the topology does not bound the node degree. A counter example is given by X.-Y. Li et al. (2003), so is an enhancement method to bound the node degree.

While all geometric structures above are flat structures, there is another set of structures, called hierarchical structures, widely used in ad hoc and sensor networks. Instead of involving all nodes to relay packets for other nodes, the hierarchical topology control protocols pick a subset of nodes to serve as the cluster-heads. These cluster-heads form a virtual backbone and forward packets for other nodes. The structure used to build this virtual

Figure 3. Examples of dominating set and k-dominating set



backbone is usually a (connected) dominating set. Many distributed clustering (or dominating set) algorithms have been proposed in the literature (e.g., Alzoubi, Wan, & Frieder, 2002; Das & Bharghavan, 1997; Wan, Alzoubi, & Frieder, 2002; Wu & Li, 1999, 2000). All these algorithms first form several clusters where all cluster-heads form a dominating set. Each node either is a cluster-head (or called dominator) or belongs to one cluster (i.e., it is dominated by a dominator). All the cluster-heads can then be connected via several additional gateways to form the virtual backbone. However, a single node failure may cause the backbone to be broken in these algorithms. Thus, a fault-tolerant design is needed for these backbones too.

Kuhn, Moscibroda, and Wattenhofer (2006) studied the *k*-dominating set (*k*-DS) problem: find a set of nodes such that each of the (other) nodes is dominated by at least *k* nodes from this set. The set of such nodes is called a *k*-dominating set. Thus, the backbone can survive (*k*-1) node failures in the *k*-dominating set. For example, black nodes v_1 and v_3 in Figure 3(b) form a DS for the network in Figure 3(a), while black nodes v_3, v_4, and v_5 in Figure 3(d) form a *2*-DS. Kuhn et al. (2006) give two distributed approximation algorithms for the *k*-minimum dominating set problem in two different models: general graphs and unit disk graphs (UDG). The first one is for general graphs and based on LP approximation. For an arbitrary parameter *t*, it runs in time $O(t^2)$ and achieves an approximation ratio of $O(t\Delta^{2/t}log\Delta)$, where Δ denotes the maximal degree. The second one is a probabilistic algorithm for unit disk graphs. It runs in time $O(loglogn)$ and achieves a constant approximation in expectation.

Dai and Wu (2005) studied how to construct a *k*-connected *k*-dominating set (*k*-CDS) as a backbone to balance efficiency and fault tolerance. Here, a *k*-DS is a *k*-CDS if its induced topology is *k*-connected. Figure 3(c) shows a CDS, and Figure 3(e) shows a *2*-CDS. Three localized *k*-CDS construction algorithms are proposed. The first one (called *k*-Gossip) randomly selects virtual backbone nodes with a given probability p_k, where p_k depends on network condition and the value of *k*. The second one is a deterministic approach based on the authors' previous method for *1*-CDS. The last algorithm (color-based *k*-CDS constriction, CBKC) is a hybrid paradigm that enables *1*-CDS algorithms to construct a *k*-CDS with high probability in relatively dense networks. It is a hybrid of probabilistic and deterministic approaches.

Besides *k*-DS and *k*-CDS, there are other techniques to enhance the fault tolerance of virtual backbones. Chen and Son (2005) present methods to add necessary redundant nodes to the simple CDS backbone, which results in a higher vertex connectivity degree. They also identify several factors and synchronization methods that may affect the redundant node selection. For example, the nodes in CDS would like to select nodes with more power or higher degree or some combination of factors. Wang, Wang, and Li (2006) propose an efficient distributed method to construct a weighted backbone with low cost. By assuming each node has a cost, they can construct a weighted CDS while the total cost of the CDS is bounded by a constant from the optimal. If each node can estimate its probability of being faulty and we treat it as the weight, we can use the algorithm by Y. Wang et al. (2006) to build a fault-tolerant backbone. Notice that building the most fault-tolerant backbone is equivalent to finding a CDS with the minimum total cost.

Most of the fault tolerant topology designs discussed so far assume the underlying communication graph is *k*-connected. This is true when the network density is large, but for sparse network it may not hold. Bredin, Demaine, Hajiaghayi, and Rus (2005) studied an interesting problem of repairing a sensor network to guarantee a specified level of connectivity. They present a generic algorithm that determines how to establish *k*-connectivity by placing minimum additional sensors geographically between existing pairs of sensors. This problem is NP-hard, and thus their algorithm is an approximation algorithm. They proved that the number of additional sensors is within a constant factor of the absolute minimum, for any fixed *k*.

A related fault-tolerant problem in two-tiered sensor network deployment is studied by Hao, Tang, and Xue (2004) and Liu, Wan, and Jia (2005). A two-tired sensor network is a cluster-based network.

Relay nodes are placed in the playing field to act as cluster-heads and to form a connected topology for data transmission in the higher tier. They are able to fuse data from sensor nodes (lower tier) in their clusters and send them to sinks through higher tier topology. Hao et al. (2004) studied a fault-tolerant relay node placement problem, where a minimum number of relay nodes are placed such that (1) each sensor node can communicate with at least two relay nodes and (2) the network of relay nodes is 2-connected. They proved the problem is NP-hard and gave a $O(Dlogn)$-approximation, where D is the diameter of the network. Notice that the ratio is not a constant but a function of the size of input. Liu et al. (2005) studied a more general relay-node placement problem where a minimum number of relay-nodes are placed in a 2-tiered sensor network such that the whole network is (1) connected or (2) 2-connected. They assumed that sensor nodes do not participate in forwarding data for others. They first gave a $(6+\xi)$-approximation algorithm for a 1-connectivity case. Then they further proposed a $(24+\xi)$-approximation algorithm and a $(6T+12+\xi)$-approximation algorithm for a 2-connectivity case, respectively, for any $\xi > 0$, where T is the ratio of the number of relay nodes placed to the number of sensors in the first case.

Thallner and Moser (2005) studied fault-tolerant overlay topology for a fully connected network. They modeled the network as a weighted complete graph, where the weight of an edge is the cost of that connection. Their proposed algorithm can build and maintain a k-regular subgraph that is k-connected and has low total weight. However, since it assumes a fully connected communication graph, the algorithm is more suitable for an overlay network (such as peer-to-peer network) than an ad hoc network.

Another fault tolerant issue in topology control is how to detect and recover from topology failures for classical topology control protocols (not the fault tolerant ones we discussed above). It focuses on the design of detection and recovering schemes instead of redundancy topology design with certain redundancy (k-connectivity). For example, Stratil (2005) presents an analysis of the requirements to tolerate crash failures in the topology with the help of failure detectors. Gupta and Younis (2003) also studied the efficient recovering mechanism for cluster-head failures. However, since fault detection and recovering are not the focus of this chapter, we do not review them in detail.

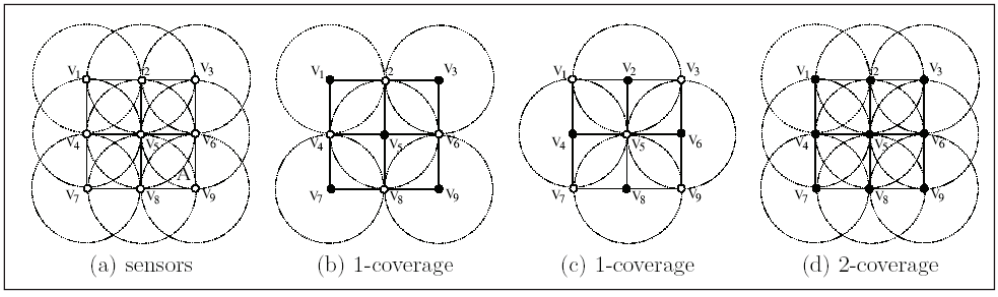
FAULT TOLERANT DESIGN IN COVERAGE AND PROTECTION

In sensor networks, coverage problem (Cardei & Wu, 2006) is also a critical issue during topology design and sensor deployment. Usually each sensor has a sensing range covering a small sensing region, and it can sense certain kinds of events happening inside its sensing region. Thus, we say the sensor covers its sensing region. The main objective of the sensor network is to cover (monitor) an area A, that is, every point in the area should be covered. Some applications may require different degrees of coverage. A network has a coverage degree k (k-coverage) if every location is within the sensing range of at least k sensors. Networks with a higher coverage degree can obtain higher sensing accuracy and be more robust to sensor failures. Given a sensor field with n sensor nodes of sensing range r deployed, and a desired coverage degree $k \geq 1$, *minimum k-coverage problem* studies how to select a minimal subset of nodes to entirely cover all locations in A such that every location is within the sensing range of at least k different nodes. The minimum k-coverage problem is also a well-known NP-hard problem. Figure 4 illustrates a set of examples of coverage set. Figure 4(a) shows the sensors and their sensing ranges. Assume that the target area A is the big square area $v_1v_3v_9v_7$. Figures 4(b) and 4(c) give two 1-coverage sets (black nodes), while Figure 4(d) gives a 2-coverage set.

Zhou, Das, and Gupta (2004) studied the minimum connected k-coverage problem and give a centralized approximation algorithm that achieves $O(\log n)$ approximation ratio. Their method is a greedy algorithm: iteratively adding a set of nodes which maximizes a measure called k-benefit to an initially empty set of nodes. The authors also present a distributed version of their algorithm.

Kumar, Lai, and Balogh (2004) studied k-coverage problem in sensor networks where many sensors are put to sleep for most of their lifetimes. They

Figure 4. Examples of k-coverage set in sensor networks



first propose a sleep/active schedule, to minimize energy consumption, in which each sensor is active with probability *p*, independently from the others. Then they derive the critical sensing range for their sleep scheme such that the sensor network achieves *k*-coverage with high probability.

Yang, Dai, Cardei, and Wu (2006) also studied the minimum connected *k*-coverage problem with different coverage assumption. They assumed that the network is sufficiently dense so that point coverage can approximate area coverage. Thus instead of covering the whole area *A*, they only required covering every sensor in area *A*. This *k*-coverage problem is also NP-hard since it is an extension of the k-dominating set problem. They propose a centralized approximation solution based on integer linear programming. The algorithm works by relaxing the problem to ordinary linear programming, where the variables may take real values. They also designed two distributed algorithms. One uses a cluster-based approach to select backbone nodes to form the active set; the other uses the pruning algorithm based on only 2-hop neighborhood information to reduce the number of active sensors.

Notice that the coverage problem studied by Yang et al. (2006) is the same problem studied by Wang, Zhang, and Liu (2006) and Wang, Li, and Zhang (2007) as *self-protection problem*. A self-protection problem focuses on using sensor nodes to provide protection to themselves instead of the objects or the area, so that they can resist the attacks targeting on them directly. A wireless sensor network is *p*-self-protected, if at any moment, for any wireless sensor (active or non-active), there are at least *p* active sensors that can monitor it. D. Wang et al. (2006) studied the minimum 1-self protection problem and give a centralized method with 2(1+*logn*) approximation ratio, using approximation algorithm for the minimum dominating set, and two randomized distributed algorithms. Wang et al. (2007) provide several efficient centralized and distributed algorithms with constant approximation ratios for the minimum *p*-self-protection problem in sensor networks with either homogeneous or heterogeneous sensing radius.

Not until recently have coverage and connectivity problems been studied together in sensor networks. Xing, Wang, Zhang, Lu, Pless, and Gill (2005) designed an integrated coverage configuration protocol to provide both certain degrees of coverage and connectivity guarantee. Zhang and Hou (2005) propose a decentralized density control algorithm to maintain sensing coverage and connectivity in high-density sensor networks. Both Xing et al. (2005) and Zhang and Hou (2005) prove that if the radio range is at least twice of the sensing range, complete *k*-coverage of a convex area implies *k*-connectivity among the working set of nodes. Recently, Bai, Kuma, Xua, and Lai (2006) studied the optimal deployment pattern to achieve both 1-coverage of an area and 2-connectivity of the sensors. Zhou et al. (2005) propose a set of distributed algorithms to achieve both *k*-connected and *k*-covered network by using localized Voronoi and extended relative neighborhood graphs.

CONCLUSION

Fault tolerance is one of the premier system design desiderata in wireless ad hoc and sensor networks.

It is crucial to have a certain level of fault tolerance in most of ad hoc and sensor applications, especially for those used in surveillance, security, and disaster relief. In addition, several network security schemes (such as localized intrusion detection) require that the underlying topology provide fault tolerance. In this chapter we discussed various fault tolerant techniques used in topology design, including those for power control, topology control, and sensor coverage. Due to space limit, we did not give all of the detailed algorithms, proofs, and simulation results for most techniques reviewed here. For more details, please refer to the references. Though fault tolerant topology design has attracted considerable attention and has been heavily studied recently, there are still many open problems, such as how to efficiently maintain these proposed fault tolerant topologies. We strongly believe that fault tolerant topology design remains one primary challenge and plays an important role in research of ad hoc and sensor networks.

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KEY TERMS

Fault Tolerance: If a network is fault tolerant or *k*-fault tolerant it means the network can survive under single or *k* node/link failures simultaneously.

K-Connectivity: If a network (graph) has *k-connectivity,* it means the it is *k*-connected, that is, given any pair of wireless devices (nodes), there are at least *k* disjoint paths to connect them.

K-Coverage: A sensor network achieves *k*-coverage if every location is covered by at least *k* different sensor nodes, *that is,* every location is within the sensing range of at least *k* different sensor nodes.

Power Control: Controls the network topology by adjusting the wireless device's transmission range to minimum energy consumption while maintaining a topology that is connected or has certain desired properties.

Self-Protection: A sensor network is *p*-self-protected, if at any moment, for any wireless sensor (active or nonactive), there are at least *p* active sensors that can monitor it.

Topology Control: Let each wireless device locally select certain neighbors for communication, while maintaining a topology that can support energy efficient routing and improve the overall network performance.

Virtual Backbone: A connected backbone formed by a subset of wireless nodes selected to perform communication tasks for the other nodes and the whole network.

Section IV

Security in Wireless PAN/LAN/ MAN Networks

Chapter XLI
Evaluating Security Mechanisms in Different Protocol Layers for Bluetooth Connections

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ABSTRACT

Security is always an important factor in wireless connections. As with all other existing radio technologies, the Bluetooth standard is often cited to suffer from various vulnerabilities and security inefficiencies while attempting to optimize the trade-off between performance and complementary services including security. On the other hand, security protocols like IP secure (IPsec) and secure shell (SSH) provide strong, flexible, low cost, and easy to implement solutions for exchanging data over insecure communication links. However, the employment of such robust security mechanisms in wireless realms enjoins additional research efforts due to several limitations of the radio-based connections, for example, link bandwidth and unreliability. This chapter will evaluate several Bluetooth personal area network (PAN) parameters, including absolute transfer times, link capacity, throughput, and goodput. Experiments shall employ both Bluetooth native security mechanisms, as well as the two aforementioned protocols. Through a plethora of scenarios utilizing both laptops and palmtops, we offer a comprehensive in-depth comparative analysis of each of the aforementioned security mechanisms when deployed over Bluetooth communication links.

INTRODUCTION

Without doubt, the Bluetooth specification (IEEE 802.15) (Bluetooth SIG, 2003; IEEE, 2002) is gradually becoming the de-facto standard for replacing short range wired communications using radio technology. According to estimations, devices incorporating Bluetooth are predicted to

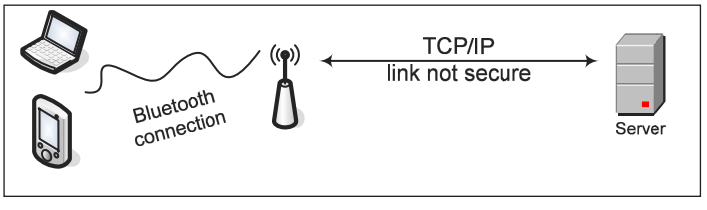
quadruple in number between now and 2008, from under 100 million to about 440 million. Bluetooth enabled devices are used in several different environments and cover a wide range of applications. For instance, for mobile applications, the device periodically connects to the network to download music, to transfer files, or to synchronize with one's desktop on calendar and other files. Consequently, the safety and security of these applications, for instance, the security of the private information stored on the devices, becomes a major issue. By attacking actively or passively the communication link, aggressors could obtain personal and also important business data. However, security features (Gehrmann, Persson, & Smeets, 2004) must be carefully considered and analyzed in order to decide whether Bluetooth technology indeed provides the right answer for any particular task or application.

The Bluetooth standard has been long criticized for various vulnerabilities and security inefficiencies, as its designers are trying to balance between performance and complementary services including security. So far, both the Bluetooth Special Interest Group (SIG) (Bluetooth SIG, 2003) and several researchers have made significant contributions on Bluetooth security aspects, discovering numerous vulnerabilities and potential weaknesses and proposing solutions (Adam, 2003; Gehrmann, & Nyberg, 2002; Jacobson & Wetzel, 2001; Persson & Manivannan, 2003; Shaked & Wool, 2005). For example, the Bluetooth pairing procedure has been anticipated to be weak under certain circumstances. Moreover, other categories of threats, either active or passive, have also been investigated, including ad hoc security issues, malicious software like "Cabir," war-nibbling, and so forth.

An obvious choice for any Bluetooth application would be to use Bluetooth encryption provided at link layer. Virtually all Bluetooth devices support this feature, and it is, in most cases, considered to be adequately secure. However, this may not be applicable for all deployment scenarios. In order to establish a secure channel with another Bluetooth device, a preshared secret called PIN is required. A symmetric key is generated from this PIN. On customer devices this PIN typically consists of four or five digits. Supposing a whole piconet network would utilize this PIN to encrypt its communication, anyone acquiring this PIN could theoretically decrypt all communication. On top of that, in applications like VoIP that mandate IP connectivity to access points (APs), the encryption would end at the AP, which means that the AP, or any host that can manipulate the communication between the Mobile Device and the other end, can expose the data (see Figure 1). Thus, it is obvious that Bluetooth encryption is not well suited for all applications which may exploit Bluetooth connections.

Under these circumstances and for certain classes of security sensitive applications deployed in Bluetooth PAN networks, the investigation of complementary and advanced security protocols apart from Bluetooth's native security mechanisms, even if deployed as an interim countermeasure, is an interesting research issue. On the other hand, as Bluetooth wireless technology is targeting devices with particular needs and constraints (e.g., processing power and battery consumption) the trade-offs between security services and performance must be carefully considered. Furthermore, considering that radio links in general suffer from limited bandwidth and are unreliable by nature, performance issues must be thoroughly investigated to make a decision whether certain security protocols and their mechanisms are advantageous over Bluetooth connections, delivering robust and agile security services within tolerable service response times.

Figure 1. Sample scenario that mandates upper layer security



During the last few years, several researchers have examined various Bluetooth security parameters and some of them do explore performance parameters (e.g., Chakraborty, 2000; De Morais Cordeiro, Sadok, & Agrawal, 2001; Francia, Kilaru, Le Phuong, & Vashi, 2004; Golmie & Rebala, 2003; Howitt, 2002; Karnik & Kumar, 2000; Kitsos et al., 2003; Lim et al., 2001; Miorandi, Caimi, & Zanella, 2003; Wang, Arumugam, & Krishna, 2002). However, to the best of our knowledge, none of these works focus on performance evaluation comparing Bluetooth's native security mechanisms with well-respected, strong security protocols like IPsec and SSH.

The chapter will focus on the performance of existing protocols and mechanisms rather than on security itself, estimating the performance of both the built-in Bluetooth security mechanisms, namely security modes, and two other standard security protocols operating at different layers of the TCP/IP protocol suite, namely SSH and IPsec. Protocols like SSH and IPsec provide robust, flexible, costless, and easy to implement solutions for exchanging data over insecure communication links. However, although their deployment is a well established and accustomed practice in the wireline world, more research effort is needed for wireless links, due to the several aforementioned limitations. Depending on the scenario involved, the user may utilize SSH or IPsec security services, either individually or in combination with Bluetooth security modes, allowing applications to communicate securely, constructing a secure tunnel. Thus, in a sense, the whole procedure can also be seen as the deployment of small VPNs in Bluetooth PANs. Note however, that the efficiency of the SSH and IPSec depends mainly on the performance of the used end-system. On the contrary, Bluetooth security native modes utilize the hardware encryption of the Bluetooth chip, thus performance depends heavily on the chip per se. This situation will allow us to make several observations about different layer security mechanisms when deployed over dissimilar user devices.

Specifically, the chapter will evaluate several personal area network (PAN) parameters, including transfer times, link capacity, and throughput. Experiments shall employ both Bluetooth native security mechanisms as well as the two aforementioned protocols. Through a plethora of scenarios, utilizing both laptops and palmtops, we intend to offer a comprehensive in-depth comparative analysis of each of the aforementioned security mechanisms when deployed over Bluetooth communication links.

The rest of the chapter is structured as follows. The next section gives an overview of our experimental test-bed related parameters and procedures, while the third section presents the derived performance measurement results. The forth section offers an analytical discussion over the conducted results. The chapter finishes with some concluding thoughts and future directions of this work.

EXPERIMENTAL FRAMEWORK DESCRIPTION

The experimental topology consists of two pairs of machines. The first pair of Bluetooth devices employs a laptop and a palmtop machine, while the other consists of two similar laptop machines. The members of each pair are located at 10 meters apart and connected via Bluetooth adapters (or built in Bluetooth chip), thus forming a small two-member wireless PAN (WPAN) or piconet. The main components' characteristics, both software and hardware, are presented in Table 1. To estimate the performance of the Bluetooth network, the data were transmitted from one network node (server) to the other (client). Hence, in order to record the incoming and outcoming packets between the corresponding network entities and to calculate the network performance parameters we utilized on the server side the well known network analyzer "ethereal" (www.ethereal.com), version 0.10.12, which in turn uses the "tcpdump" tool. In addition, for the Linux environment, we employed the BlueZ official Linux Bluetooth protocol stack (www.bluez.org), which provides support for the core Bluetooth layers and protocols.

Bluetooth supports three different security modes called security modes I, II, and III, but in

our tests we decided to use only security modes I and III. Security mode I offers no real security as authentication and confidentiality services are disabled. On the other hand, security mode II provides security services after the connection between the two devices has been established and only if a given application has requested them. Thus, the security services in mode II depend on the application running. The last security mode is the most powerful among the three modes because it mandates both authentication and confidentiality built-in mechanisms independently of the application running. These mechanisms are referred to as Bluetooth baseband security procedures, where the baseband layer deals with the SAFER+ algorithms (Massey, Khachatrian, & Kuregian, 1998). As implied, one of the terminals was acting as a client and the other one as the server. Therefore, the server should require security and the client should respond accordingly.

For IPsec, the engaged machines must have the same security policies in order to communicate securely. So, we configured Linux to use MD5 and SHA1 algorithms for data integrity and DES and 3DES algorithms for confidentiality in both machines by installing IPsec-tools (http://ipsec-tools.sourceforge.net/) and Openswan (www.openswan.org) as well. For SSH secured communication we used OpenSSH. In fact, many open-source projects exist. In addition to FreeSWAN and openswan which both enable IPsec in the Linux kernel, openvpn (http://openvpn.net/) can be used to create TLS-encrypted point-to-point connections. For SSH confidentiality services we chose four algorithms to test namely, 3DES, AES, Arcfour, and Blowfish. Finally, for both IPsec and SSH we employed only symmetric cryptography and manual keying procedures for the authentication of parties considering the fact that usually Bluetooth piconets are formed ad hoc and their users do not hold public key certificates.

PERFORMANCE MEASURES

As mentioned before, the experimental procedure consists of three main parts: evaluation of Bluetooth built-in security modes I (no security), and III

Table 1. Hardware and software characteristics of the engaged machines

First pair	Laptop Server	
	Processor	Intel Celeron M. – 1.4 GHz
	RAM	256 MB
	Operating System	SUSE Linux Ver. 10.0
	Bluetooth Adapter	Trust Bluetooth adapter Class 1
	Palmtop Client	
	Model	HP iPAQ h5400
	Processor	400 MHz Intel XScale PXA250
	RAM	64 MB
	Operating System	Familiar PDA OS 0.8.4
	Bluetooth Adapter	Bluetooth 1.1 compliant

Second pair	Laptop client and server	
	Processor	Intel Celeron M. – 1.4 GHz
	RAM	256 Mbytes
	Operating System	SUSE Linux Ver. 10.0
	Bluetooth Adapter	Trust Bluetooth adapter Class 1

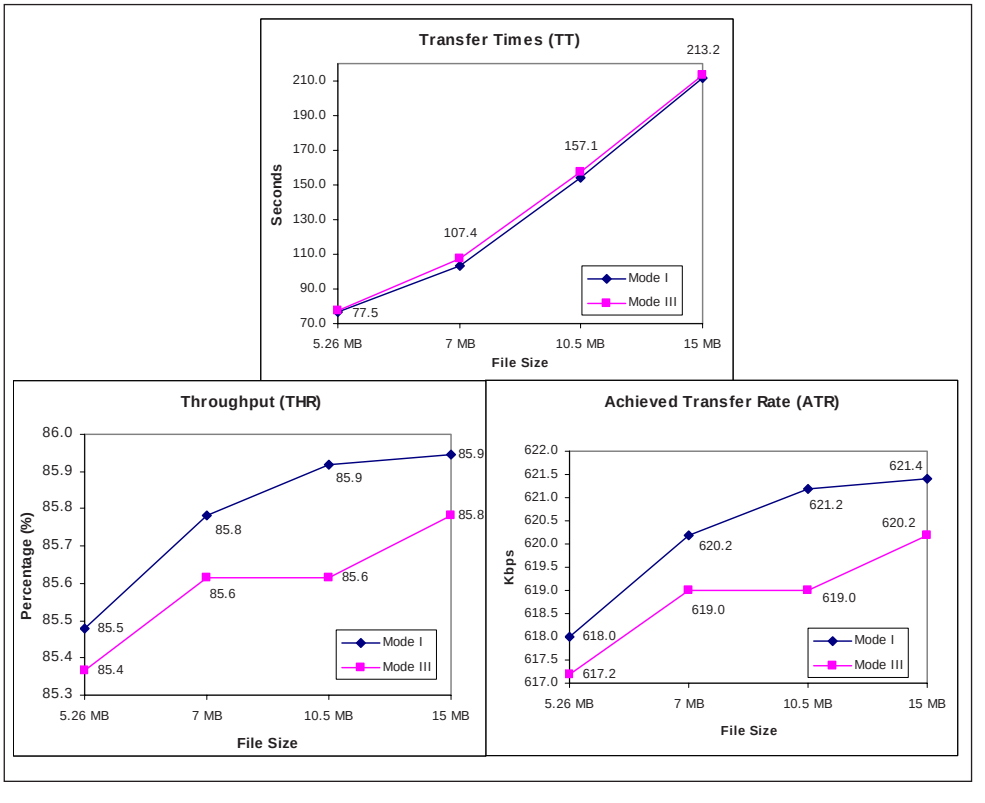
(strong security), and estimation of the performance of IPsec and SSH mechanisms over Bluetooth links. In all scenarios we gathered measurements for the subsequent network performance parameters: absolute file transfer time (TT), achieved transfer rate (ATR), and throughput (THR). All measurements took place at the server node because of its processing power.

- The *Transfer_Time* represents the actual duration of transfers during a transaction.
- The *Achieved_Transfer_Rate* represents the actual transfer rate achieved during a transaction. In an ideal scenario, a constant data rate should be maintained between the two communication end-points. However, due to various reasons, mainly related to the wireless medium nature, this parameter is changing over time. We should underline the fact that bytes_sent and bytes_received could also contain retransmitted bytes.

  Achieved_Transfer_Rate(Kbps) = ((bytes_sent + bytes_received) * 8) / TT
- Throughput represents the percentage of Achieved_Transfer_Rate over the practical maximum_transfer_rate of the link, which in our case is 723 Kbps:
  Throughput(%) = achieved_transfer_rate / max_transfer_rate * 100
- Finally, *Achieved_Transfer_Rate_Improvement* is a comparison metric that indicates the improvement of the Achieved_Transfer_Rate with respect to the Bluetooth mode I achieved transfer rate Achieved_Transfer_Rate_B_I and is calculated as:
  Achieved_Transfer_Rate_Improvement(%) = (ATR - ATR_B_I) / ATR_B_I * 100

A positive value implies that the performance (or channel throughput) has increased compared to the Bluetooth mode I achieved transfer rate, while a negative one means that the performance has

Figure 2. Average metric values for network parameters measured/Bluetooth Modes I and III



decreased. Measurements were gathered during repeated FTP file transfers, between the laptop server and the PDA client from the one hand and between the laptop client and server from the other. Each file was transferred twelve times and only average values were recorded. In all scenarios, the ping response times between client and server were varying among 19.7 and 21.8msecs. Due to space limitations, in the following first three subsections we present only the analytical results derived from the laptop server/PDA client, which is without doubt the most interesting one, while some indicative corresponding comparisons with the other laptop client–server pair is exhibited in the subsection titled "Comparison Between PDA and Laptop Clients."

Bluetooth Security Modes I and III Evaluation

Measurements for testing Bluetooth modes I and III were gathered by transferring four different files between each client–server pair. The files' sizes were 5.26, 7.0, 10.5, and 15 Mbytes, respectively. Figure 2 provides a graphical representation of these values comparing TT times achieved in the PDA client–laptop server piconet. As we can easily notice, the results are generally as expected, but there are some interesting points which need further analysis. At first, the TT metric is slightly higher for mode III, as well as the ATR is higher for mode I. This happens because mode III mandates authentication (handshake) at the beginning of each transaction. Keep in mind that the handshake time is included in TT too.

Moreover, encryption algorithms are applied during the transaction for mode III and as a result the overall transfer time is increased. We can also perceive that the larger the file size is, the longer the TT difference between mode I and mode III is expected to be. This situation is also depicted in the respective plot of Figure 2. In general, these measurements advocate that mode I utilizes the network better than mode III. Because of the volatile nature of the wireless link, we also report standard deviation (SD) for the measured values in Table 2.

Secure Shell (SSH) Evaluation

Experimental procedures for the SSH mechanism (IETF, 2006; OpenSSH, 2006) consider the transfer of the same four files, as before, between the client and the server. Table 3 displays the average times of all metrics used, while Table 4 presents the corresponding standard deviation values.

As we can notice, SSH gives highly increased transfer times when compared to Bluetooth security modes. For instance, we can spot a difference of +12.6 seconds to +13.4 seconds for the smallest file depending on the cipher used. Moreover, it is more than obvious that all the ciphers used are more or less of the same performance. This is easily proven if we examine for example the achieved transfer rates in each case, which shown very slight differences.

Another interesting assumption that we can make is that as the size of the file increases, the achieved transfer rate and the throughput become bigger. This happens because of the procedure of the authentication which takes place during the ini-

Table 2. Standard deviation for all Bluetooth scenarios

	MODE I			MODE III		
File Size (MB)	TT (sec)	ATR (Kbps)	THR (%)	TT (sec)	ATR (Kbps)	THR (%)
5.26	0.5	2.6	0.4	0.1	1.3	0.2
7	0.1	0.9	0.1	0.5	3.2	0.4
10.5	0.4	1.6	0.2	0.1	0.5	0.1
15	0.2	0.5	0.1	0.6	2.2	0.3

Table 3. Average values for network parameters measured (SSH)

	5.26 MB			7 MB		
	TT (sec)	ATR (Kbps)	THR (%)	TT (sec)	ATR (Kbps)	THR (%)
3DES	90.1	526.4	72.8	116.9	555.6	76.9
AES128	90.2	525.6	72.7	116.9	556.2	76.9
Arcfour	90.5	523.8	72.5	117.3	554.2	76.6
Blowfish	90.5	523.6	72.4	117.6	552.8	76.4
	10.5 MB			15 MB		
3DES	163.0	581.8	80.5	221.3	603.2	83.4
AES128	162.9	582.4	80.5	221.3	603.6	83.5
Arcfour	163.1	581.6	80.5	221.6	602.4	83.3
Blowfish	162.8	582.6	80.6	222.1	601.2	83.1

Table 4. Standard deviation for all SSH scenarios

	5.26 MB			7 MB		
	TT (sec)	ATR (Kbps)	THR (%)	TT (sec)	ATR (Kbps)	THR (%)
3DES	0.4	2.1	0.3	0.4	2.1	0.3
AES128	0.9	5.5	0.7	0.4	1.9	0.2
Arcfour	0.1	0.4	0.1	0.2	1.1	0.2
Blowfish	0.6	3.8	0.5	1.0	4.9	0.7
	10.5 MB			15 MB		
3DES	1.0	3.3	0.5	0.8	2.5	0.3
AES128	1.0	3.9	0.5	0.9	2.3	0.3
Arcfour	0.5	1.9	0.3	0.6	1.7	0.2
Blowfish	0.6	1.9	0.3	0.7	1.9	0.3

tial SSH handshake. In any case it should be noted that the improvement in the achieved transfer rates always compared to Bluetooth security mode I and induced by SSH, are negative for any scenario. This means that Bluetooth's native mechanisms offer better bandwidth and network utilization at almost all cases examined. This remark is confirmed by the values given in Table 5.

IPsec Evaluation

The procedure for the IPsec protocol (Kent & Atkinson, 1998a, 1998b) considers once again the transfer of the same four files between the client and the server. IPsec uses two mechanisms (protocols) that may be used independently or jointly to secure the outcoming traffic, namely authentication header (AH) offering data origin, connectionless

Table 5. %ATR deterioration for SSH

Size	Bluetooth Mode I	3DES	AES128	RC4	Blowfish
5.26	618.0	-14.8	-15.0	-15.2	-15.3
7	620.2	-10.4	-10.4	-10.6	-10.9
10.5	621.2	-6.3	-6.2	-6.4	-11.0
15	621.4	-2.9	-2.9	-3.3	-3.3

Table 6. Average values for network parameters measured (IPsec)

	5.26 MB			7 MB		
	TT (sec)	ATR (Kbps)	THR (%)	TT (sec)	ATR (Kbps)	THR (%)
AH_MD5	72.8	683.4	94.5	100.0	682.8	94.4
AH_SHA1	72.8	683.2	94.5	99.9	683.0	94.5
ESP_DES_MD5	74.4	681.0	95.0	102.0	686.6	95.0
ESP_3DES_MD5	73.8	681.0	95.7	102.2	685.2	94.8
ESP_DES_SHA1	74.2	680.0	95.2	102.0	686.6	95.0
ESP_3DES_SHA1	74.2	681.0	95.2	101.8	688.2	95.2
	10.5 MB			15 MB		
AH_MD5	145.9	682.6	94.4	205.2	683.4	94.5
AH_SHA1	145.7	683.4	94.5	205.1	683.8	94.6
ESP_DES_MD5	148.6	688.2	95.2	208.9	688.8	95.3
ESP_3DES_MD5	148.6	687.8	95.1	209.1	688.0	95.2
ESP_DES_SHA1	148.5	688.4	95.2	209.2	688.0	95.2
ESP_3DES_SHA1	148.6	688.0	95.2	210.5	683.6	94.6

Table 7. Standard deviation of measurements of all IPsec scenarios

	5.26 MB			7 MB		
	TT (sec)	ATR (Kbps)	THR (%)	TT (sec)	ATR (Kbps)	THR (%)
AH_MD5	0.0	0.5	0.05	0.1	0.8	0.12
AH_SHA1	0.1	0.4	0.1	0.1	0.0	0.05
ESP_DES_MD5	0.1	0.4	0.1	0.3	2.1	0.28
ESP_3DES_MD5	0.5	4.5	0.6	1.3	8.6	1.19
ESP_DES_SHA1	0.0	0.4	0.06	0.6	3.7	0.53
ESP_3DES_SHA1	0.0	0.4	0.06	0.1	0.4	0.1
	10.5 MB			15 MB		
AH_MD5	0.1	0.5	0.06	0.2	0.5	0.08
AH_SHA1	0.2	0.9	0.1	0.1	0.4	0.03
ESP_DES_MD5	0.1	0.8	0.09	0.1	0.4	0.04
ESP_3DES_MD5	0.1	0.8	0.08	0.1	0.0	0.03
ESP_DES_SHA1	0.0	0.5	0.02	0.3	1.0	0.13
ESP_3DES_SHA1	0.1	0.7	0.06	2.4	7.6	1.05

data integrity, and optionally replay protection, and encapsulating security payload (ESP) offering confidentiality and protection against traffic analysis. In our scenarios we utilized both mechanisms, using the MD5 and SHA1 algorithms for integrity and DES and 3DES to support confidentiality services. Note however that MD5 is not considered secure anymore and is reported here for the sake of completeness. In total, we deployed six scenarios as shown in Table 6.

First and foremost, all network metrics for IPsec are remarkably concentrated. Standard deviation

values rendered in Table 7 confirm this remark. Surprisingly, IPsec gives better transfer times for all file sizes when compared to Bluetooth and SSH. This is also confirmed by %ATR improvement for IPsec shown in Table 8. In particular, all IPsec times are very close to those of Bluetooth's mode I, while at the same time are considerably better than SSH's. Note, that IPsec renders 210.5 seconds as the highest time duration for transferring the biggest file, while correspondingly SSH gives 222.1 seconds, mode III produces 213.2 seconds, and mode I 211.6 seconds. This is partially due to substantially increased (and highly stabilized) bandwidth that IPsec generates. The aforementioned observations are also confirmed by the fact that during IPsec measurements we had a very low rate of packet loss reported by the Ethereal utility. It is important to note that the throughput was better when using ESP. On the contrary, when using AH, the throughput for transferring the files was lower. This can be explained by the fact that authentication is applied in AH.

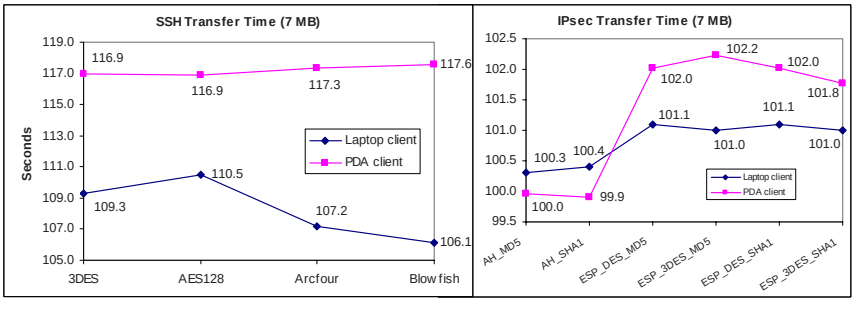
Comparison Between PDA and Laptop Clients

Considering the second experimental pair, which employs laptops for both the server and the client (see Table 1), TT times were better for all the corresponding scenarios, namely Bluetooth native security modes, SSH and IPsec. For instance, Bluetooth modes show a slight TT improvement ranging from 1 to 3 seconds depending on the file size. Specifically, TT for the 7 MB file was 102.8 and 106.5 for Bluetooth mode I and III, respectively. Approximately the same situation is reported for SSH and IPsec as depicted in Figure 3. This is expected as the laptop client incorporates a faster CPU and thus gains more in cryptographic operations that SSH and IPsec mandate. The same remark is applied for the other two network performance parameters, throughput and ATR. As in the PDA client case, IPsec continues to perform better under all circumstances for the laptop client due to its throughput optimization. However, IPsec

Table 8. % ATR improvement for IPsec

		AH_		ESP_DES_		ESP_3DES_	
File Size	Bluetooth Mode_I	MD5	SHA1	MD5	SHA1	MD5	SHA1
5.26	618.0	10.6	10.6	11.1	11.4	11.9	11.4
7	620.2	10.1	10.1	10.7	10.7	11.5	11.0
10.5	621.2	9.9	10.0	10.8	10.8	10.7	10.8
15	621.4	10.0	10.0	10.8	10.7	10.7	10.0

Figure 3. Comparison of network transfer times between Laptop and PDA clients



TT times remain very close to those of Bluetooth security modes. The same situation is confirmed by the minimum standard deviation values that characterize the IPsec case. Also in this case, SSH gives the worst performance compared with IPsec and Bluetooth native security modes.

COMMENTS ON THE RESULTS

This section provides a comparative view of the conducted results. Also, we attempt to provide a better explanation of the experiment outcomes. But before that we must shortly discuss important characteristics of Bluetooth connections that may affect the performance of the connection. Bluetooth employs frequency hopping spread spectrum (FHSS) to avoid interference. There are 79-23 in some countries-hopping frequencies, each having a bandwidth of 1MHz. Frequency hopping is assisted with fast automatic repeat request (ARQ), cyclic redundancy check (CRC), and forward error correction (FEC) to achieve high reliability on the wireless links. All the data/control packet transmissions are synchronized by the master. Slave units can only send in the slave-to-master slot after being addressed in the preceding master-to-slave slot, with each slot lasting 625 microseconds.

For real-time data such as video, synchronous connection oriented (SCO) links are used, while for data transmission, asynchronous connectionless link (ACL) links are employed. There are several ACL packet types, differing in packet length and whether they are FEC coded or not. The FEC coding scheme used in ACL DM mode is a shortened Hamming code, where each block of 10 information bits is encoded into a 15 bit codeword, and is capable of correcting single bit error in each block. Table 9 shows the different ACL packet types and their properties. The values in the table are theoretical without packet overhead. For example, over an ACL link using DH5, one can send about 300 to 320 kbit/s of UDP user data, while the theoretical limit is 433.9 kbit/s.

This means that in order to overcome the effect of low and varying link quality on throughput, the selection of the optimal link layer packet size, under estimated channel conditions, is crucial. Indeed some research work (Chen, Kapoor, Sanadidi, & Gerla, 2004) points this out by evaluating the "optimal" link layer packet size based on the current bit error rate of the channel. Moreover, in regions that Wi-Fi networks coexist with Bluetooth and because Wi-Fi and Bluetooth utilize spectrum in different ways, they can cause considerable interference between each other (depending on the relative location of the 802.11b and Bluetooth devices) (Yip & Kwok, 2004). By transmitting at the highest power level, Bluetooth class 1 devices would create more interference than Bluetooth's class 2 and class 3 devices, which transmit at lower power levels. Furthermore, because each Bluetooth PAN will occupy the entire ISM band, two or more coexisting Bluetooth PANs will occasionally collide, possibly causing loss of data packets. Of course, apart from implementation issues (e.g., protocol stacks), the aforementioned parameters are closely related and can affect real Bluetooth connections and the results gathered in this chapter. For instance, all experiments were conducted inside the coverage area of the University's hot-spot.

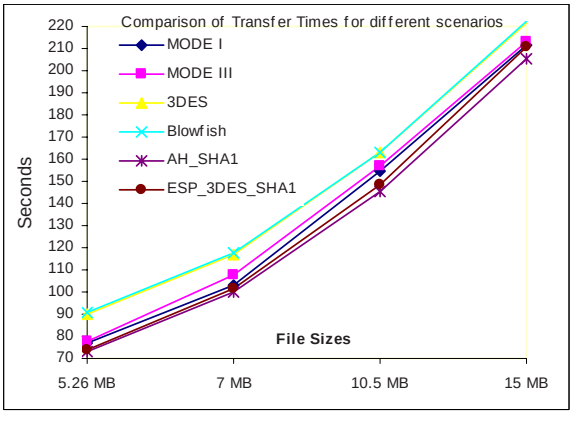
Table 9. Packet types for Bluetooth ACL Connections (theoretical values)

Mode	FEC	Packet (bytes)	Size (kbps)	Symmetric (kbps)	Asymmetric (kbps)
DM1	2/3	0-17	108.8	108.8	108.8
DM3	2/3	0-121	258.1	387.2	54.4
DM5	2/3	0-227	286.7	477.8	36.3
DH1	no	0-27	172.8	172.8	172.8
DH3	no	0-183	390.4	585.6	86.4
DH5	no	0-339	433.9	723.2	57.6

In the following, we present comparative graphs only for two of the three network parameters, transfer times, and throughput for the PDA client. As already noted in "Comparison between PDA and Laptop Clients," the laptop client scenario results are directly comparable with those of the PDA client and thus do not contribute further to this discussion. Consequently, Figure 4 illustrates a comparison of the transfer times for six selected scenarios in total. We easily spot that all times, especially for file sizes smaller than 10.5 MB, seem to be highly concentrated. This means that (excluding SSH ones) we have marginal differences between the performances' of the conducted scenarios. But, the bigger the size gets, the difference tends to slightly decrease. Apart from the fact that all tests have the Bluetooth link parameter in common, this can be explained by the fact that Bluetooth modes and IPsec utilize the network better.

On the downside, SSH does not always provide peak network performance because it traditionally has been more focused on providing security. In a nutshell, SSHv2 introduced an additional form of flow control that requires the receiver to ACK each packet before more packets can be sent. Most implementations seem to use packet sizes of 16K or occasionally 32K, with some going as low as 4K. This means that no matter how fast the link, every for example, at 16K the transmission stops for one round trip time awaiting the other side to send its ACK (referred to as a window adjust in SSHv2 terminology). In addition to the protocol-level handbrake, the SSH file transfer protocol (SFTP) that runs on top of SSH contains its own handbrake. This protocol recommends that reading and writing is limited to less than 32K of data, even though it is running over the reliable SSH transport which in turn runs over the reliable TCP/IP transport. One common implementation limits SFTP packets to 4K bytes, resulting in a mere 4% link utilization in the previously-presented scenario.

Figure 4. Comparison of network transfer times for six different scenarios (PDA client)



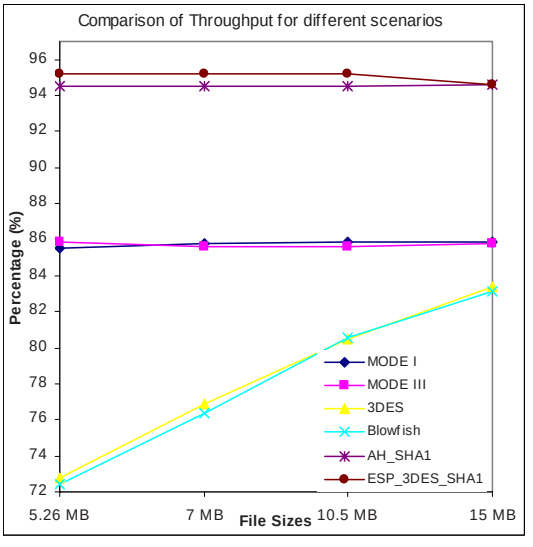
Finally, Figure 5 depicts a comparison of the achieved throughput for the specific six scenarios. This plot gives a clearer idea about the achieved network performance. In short, IPsec scenarios visibly have the best performance by far followed closely by the two Bluetooth's security modes. Moreover, we can make a very important observation about the SSH's performance. It is obvious that SSH's throughput increases as the file's size increases. This happens because of the handshaking phase which takes place during the initialization of each transaction. So, as the size of the transferred file increases, the impact of handshaking decreases and thus we notice an increase in the throughput. We should also report that the throughput of the other two scenarios remains more or less stable for all the file sizes we utilized. Another important issue is that during the experiments we observed a significant rate of packet loss for both Bluetooth security modes and SSH scenarios affecting their overall performance. Certainly, the main reason for this is the volatile nature of the wireless connection itself.

Additionally, it is well known that the addition of an IPSec header may cause IP fragmentation. However, the main concern in IPsec overhead is in the encryption, decryption, and authentication of the actual IPsec (ESP and/or AH) packets. Tunnel setup and rekeying occur much less frequently than packet processing and, except in highly unusual circumstances, their overheads are not worth worrying about. According to some other works (e.g., FreeSwan, 2002) utilizing low-end machines, a 60 MHz Pentium running a host-to-host tunnel to another machine shows an FTP throughput of slightly over 5 Mbit/s either way. Thereafter, we can conclude that in our case the IPsec mechanisms running on "relatively" low-end processors is not

really a bottleneck. The overall performance is rather affected most by the quality of the Bluetooth link itself, meaning that due to better utilization of the link and possibly due to optimal ACL scheme and lower packet drop rate, IPsec performs slightly better than native Bluetooth modes do.

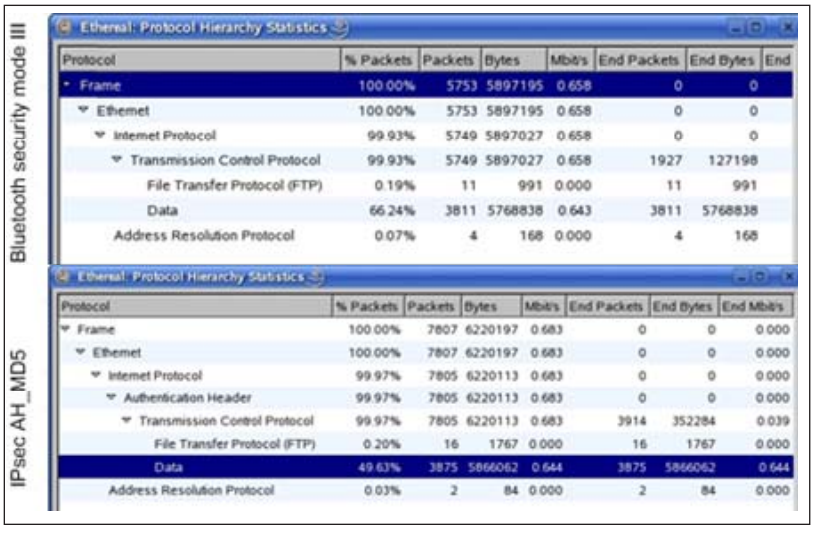
In Figure 6, we present some indicative ethereal screens that attest why in practice IPsec performs better from the other two in terms of the additional protocol overhead induced. These screens illustrate the overall network statistics for Bluetooth mode III and IPsec AH_MD5, respectively. The "Data" section corresponds to the overall percent of data that were sent from the server towards the PDA client for the 5.26 MB file. We observe that IPsec needs considerably lower percent of TCP data packets to complete the transaction (49.63%) than Bluetooth mode III which requires 66.24%. Note, that excluding ARP messages, the remaining percent corresponds to control information sent from the client to the server including ACKs, retransmissions, and so forth. Therefore, IPsec utilizes the link better, achieving higher performance.

Figure 5. Comparison of network throughput for six different scenarios (PDA client)



Another important factor that may affect the conducted results is the operating system itself. For that we performed partial measurements using the Windows XP operating system in the laptop client, while keeping all the other test-bed parameters unchanged. Under this setting, we observed significantly lesser packet retransmissions and logged fairly better times. For example, for Bluetooth mode III and file size 10.5 MB we got an average transfer time of 150 seconds, namely 5 seconds better than Linux. One can presume that the Bluetooth stack is better implemented in Windows than in Linux or the Bluetooth adapters that we used perform better under Windows, perhaps due to their drivers' implementation. Nevertheless, a detailed analysis of this

Figure 6. Ethereal screens with protocol hierarchy statistics (PDA client)



behavior between the two major operating systems is necessary but left for future work. An additional interesting research question is whether the recent updates of the Bluetooth specification to version 1.2 that have introduced significant changes in the Bluetooth protocol stack, including optional flow control, can affect the performance of the security mechanisms under investigation (Misic, Chan, & Misic, 2005). However, this is out of scope of the current chapter.

For the laptop client we also provide some indicative metrics concerning the physical memory consumption for the three categories of scenarios. More specifically, memory consumption for Bluetooth modes I and III was 552 KB, which is the "pand" daemon. For SSH we have an additional 1920 KB, thus in total 2472 KB ("sshd" and "pand" deamons), and finally for the IPsec case we have 4027 KB ("pluto" and "pand" daemons).

CONCLUSION AND FUTURE WORK

This chapter addresses performance issues for Bluetooth host-to-host connections. Three distinct categories of scenarios were used to test whether well respected security mechanisms of Internet and application layers of the TCP/IP suite are advantageous when deployed over Bluetooth PANs compared to Bluetooth native security modes. The results disclose that IPsec better utilizes the wireless link and thus provides radically improved transfer times when compared with SSH. Native Bluetooth modes service times are close to those of IPsec's thus significantly better from SSH ones. On the other hand, there is an important disadvantage which is the high amount of the memory resources IPsec consumes.

As future work we would like to expand this study, investigating the performance of asymmetric cryptography mechanisms, for example, public key certificates, and to support authentication services in the context of such protocols that promote automatic keying. Another direction is to detect how much energy is required for this sort of secure connections, as mobile devices can not afford batteries with unlimited capacity.

ACKNOWLEDGMENT

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KEY TERMS

Bluetooth: An industrial specification for wireless personal area networks (PANs). Bluetooth provides a way to connect and exchange information between devices such as mobile phones, laptops, PCs, printers, digital cameras, and video game consoles via a secure, globally unlicensed short-range radio frequency.

Goodput: The application level throughput, that is, the number of useful bits per unit of time

forwarded by the network from a certain source address to a certain destination, excluding protocol overhead retransmissions, and so forth.

IEEE 802.15: The IEEE 802.15 WPAN working group focuses on the development of consensus standards for personal area networks or short distance wireless networks. These WPANs address wireless networking of portable and mobile computing devices such as PCs, PDAs, peripherals, cell phones, pagers, and consumer electronics, allowing these devices to communicate and interoperate with one another. The IEEE Project 802.15.1 has derived a wireless personal area network standard based on the Bluetooth v1.1 Foundation Specifications.

IPsec: IPsec (IP security) is a suite of protocols for securing Internet protocol communications by encrypting and/or authenticating each IP packet in a data stream. IPsec also includes protocols for cryptographic key establishment. There are two modes of IPsec operation: transport mode and tunnel mode. IPsec is implemented by a set of cryptographic protocols for securing packet flows. Specifically, the authentication header (AH) protocol provides authentication, payload (message), and IP header integrity (with some cryptography algorithm also nonrepudiation). On the other hand, the encapsulating security payload (ESP) protocol provides data confidentiality, payload (message) integrity, and with some cryptography algorithm also authentication.

Network Performance: The level of quality of service of a telecommunications resource, protocol, or product.

Secure Shell or SSH: A set of standards and an associated network protocol that allows establishing a secure channel between a local and a remote computer. It uses public-key cryptography to authenticate the remote computer and to optionally allow the remote computer to authenticate the user. SSH provides confidentiality and integrity of data exchanged between the two computers using encryption and MACs.

Throughput: The amount of digital data per time unit that are delivered to a certain terminal in a network, from a network node, or from one node to another, for example, via a communication link.

Chapter XLII
Bluetooth Devices Effect on Radiated EMS of Vehicle Wiring

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ABSTRACT

The electromagnetic energy source used by wireless communication devices in a vehicle can cause electromagnetic compatibility problems with the electrical and electronic equipment on board. This work is focused on the radiated susceptibility (electromagnetic susceptibility [EMS]) issue and proposes a method for quantifying the electromagnetic influence of wireless radio frequency (RF) transmitters on board vehicles. The key to the analysis is the evaluation of the relation between the electrical field emitted by a typical Bluetooth device operating close to the automobile's electrical and electronic systems and the field level specified by the electromagnetic compatibility (EMC) directive 2004/104/EC for radiated susceptibility tests. The chapter includes the model of a closed circuit structure emulating an automobile electric wire system and the simulation of its behaviour under electromagnetic fields' action. According to this a physical structure is designed and implemented, which is used for laboratory tests. Finally, simulated and experimental results are compared and the conclusions obtained are discussed.

INTRODUCTION AND BACKGROUND

In the current vehicle coexist electronic and communications systems whose advantages are clear for the user but whose possible problems are not contrasted. The increasing use of radio frequency transmitters by automobile users makes it necessary to evaluate the risk caused by the coexistence of information and communication technologies in the reduced space inside the vehicle. In this

context, the present work appears in order to bring up methods and results that contribute to establishing the possible risks limit of the use of wireless devices inside the automobile, and more precisely those based on Bluetooth technology.

To centre the problem, it is mentioned the tendencies in the automobile field that bet for the incorporation of new electrical and electronic systems (X-by-Wire technology) (Leen & Hefferman, 2002; Mazo, Espinosa, Awawdeh, & Gardel, 2005) front of the current mechanical systems, aspects of automotive electromagnetic compatibility (EMC) standard 2004/104/EC (2004) for evaluation of susceptibility/immunity in vehicles are detailed, it is justified the interest to focus the study on the extended Bluetooth wireless communication technology. However there are nonregulated questions by the 2004/104/EC concerning the use of Bluetooth devices what rise uncertainties around the risk derived from its use.

To get a better knowledge of this issue, we lay a few questions regarding the increase of the electronic equipment role in the automobile, the characteristics of commercial Bluetooth devices, some notes about the EMC European Directive involved in vehicles, and last but not least, some of the directive gaps concerning Bluetooth wireless devices in this context.

The Increase in Electrical and Electronic Components in Automobiles

It is clear that nowadays on board electronic components play an important role on vehicles (Bannatyne, 2000; Leen & Hefferman, 2002; Mazo et al., 2005), as much for the increase in the number of electronically controlled units (ECUs) as for the complexity of the communication system (field buses) implemented.

Continuous development in the industrial automobile sector means that dynamic systems that have traditionally been of a mechanical and hydraulic nature, such as the steering, braking, and acceleration are being replaced by electronic ones, which leads to the proposal of networks such as X-by-Wire with its own protocol (Mazo et al., 2005).

Taking advantage of the trend towards the use of DC voltage supplies of 36-42 volts instead of the 12-14 volts currently used, an increase in electronics is being adopted to control key elements of the automobile such as the steering, braking, and acceleration. For example, the car uses a range of electric actuators and also has an innovative driver interface. The driver has all the vehicle functionality in a special steering wheel, which is used for acceleration and braking as well as for steering and gear shifting. The vehicle uses a conventional engine for propulsion but electromechanical actuators for braking, clutching, and gear shifting (Larses, 2003).

With the progress of X-by-Wire technology, in-vehicle data traffic is always growing. Conventionally, individual wire harnesses were used for data transfers between control units and their associated sensors or display devices. As the number of control units and associated devices increase, the number of wire harnesses and interconnections required is swelling. The in-vehicle local-area network (controller area network [CAN], local interconnect network [LIN], and FlexRay) provides an answer to this problem: it minimises the use of individual wire harnesses for data exchanges and reduces both interconnections and vehicle weight, trying to improve consumption, power, security, and comfort.

However, associated with these electronic and communication innovations new sources of potential equipment failure appear, leading to the necessity to continue working on both diagnosis and prognosis in the automotive sector.

Bluetooth Devices and Applications in Automobiles

The presence of radio frequency transmitters in automobiles as a way for multiple wireless communication appliances continue to grow. Apart from the well known uses for the assistance and entertainment (GPS, laptops, PDAs, digital cameras, portable multimedia devices CD/DVD, etc.), others such as remote diagnosis, traffic control, accident assistance, and so forth are being promoted (Campos, Mills, & Graves, 2002; Mazo et al. 2005).

There are several wireless technologies (WiFi, DSRC, Zigbee, etc.) available to automobile manufacturers and users, but at present the most widely used is Bluetooth. Although the functionality and operativity of each technology is different, they have in common the incorporation of a transmitter or an electromagnetic energy source in the environment in which they operate. This extra energy can cause any kind of failure on equipment situated close to the transmitter, as is the case of ECUs on board a vehicle where the driver introduces several wireless devices. At the same time, the metal cage of the vehicle can act as a concentrating reflector, amplifying radio frequency (RF) density emitted by different radiation sources to higher and potentially more dangerous levels.

Bluetooth is an open technology that works with low power and is designed for short range (10 m-100 m), leading to being widely used in transport applications in general and in automobiles in particular. The operating frequency range is within the industrial, scientific, and medical (ISM) bandwidth used of 2.4 GHz to 2.4835 GHz. The frequency range is divided into 79 individual RF channels, each one separated by 1MHz. The output levels are divided into three classes (SIG, 2006): class I (100 mW, +20 dBm), class II (2.5 mW, +4 dBm) and class III (1 mW, 0 dBm).

The equation that determines the frequency for each one of the channels is as follows:

$$F(MHz) = 2402 + k \qquad \text{where, } k = 0\ldots..78$$

In order to comply with out of band regulations in each country, a lower guard band of 2 MHz and an upper guard band of 3.5 MHz are used. The protocol uses a spread spectrum, or in other words, the transmission frequency changes randomly 1,600 times per second, reducing this way the possible interferences created by different transmitters working at the same time in the same frequency range.

Equipments transmit and receive using a time division multiplex (TDM). In addition, spread spectrum TDM provides a higher degree of security against eavesdropping and provides resilience to ambient noise. GFSK modulation is used in Bluetooth technology, where a logic 1 level is represented by a positive frequency shift and a logic 0 level is represented by a negative frequency shift. Keeping all this in mind, a Bluetooth transmitter, from an EMC viewpoint, can be considered as an interfering RF source in the 2.4 to 2.4835 Ghz frequency band.

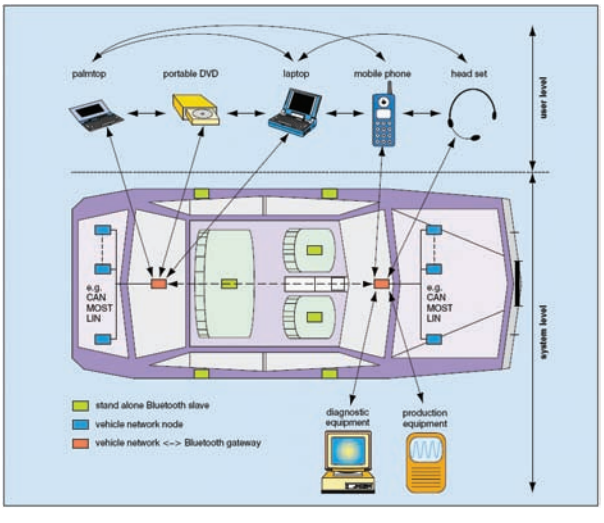
Two levels of Bluetooth technology application can be considered inside an automobile: Bluetooth integrated into the vehicle at a system level and Bluetooth at a user device level. From a user device level point of view, Bluetooth technology allows connecting inside the vehicle electronic mobile devices such as PDAs, laptops, GPSs, handsfree sets, or cell phones, as seen in Figure 1.

The concept of 'Bluetooth integrated into the vehicle at a system level' is used when a Bluetooth network can provide a functionality and versatility similar to a vehicle control cabled network (e.g., CAN bus) which is nowadays the most widely extended solution (network and protocol) in vehicles.

Directive 2004/104/CE for the Assessment of EMC in Vehicles

In Europe, EMC activity in automobiles is regulated by the recent directive on electromagnetic

Figure 1. Typical applications of Bluetooth in vehicles



compatibility (2004/104/EC EMC, 2004), which since July 1, 2006, substitutes the earlier directive (95/54/EC EMC, 1995). The new directive requires tests to be carried out at both component level and on the vehicle as a whole. The range of required tests includes broadband and narrowband radiated emissions (CISPR 12, 2001; CISPR 25, 2002; Kerry, 2003), radiated susceptibility (ISO 11452-2, 2004), as well as conducted susceptibility and emissions along supply lines of electrical and electronic subcomponent (ISO 7637-2, 2004).

The present article focuses on the radiated susceptibility test in accordance with regulation ISO 11452-2 as this test allows determining the electromagnetic immunity of a device or electronic component on board the vehicle in proximity to RF transmitters.

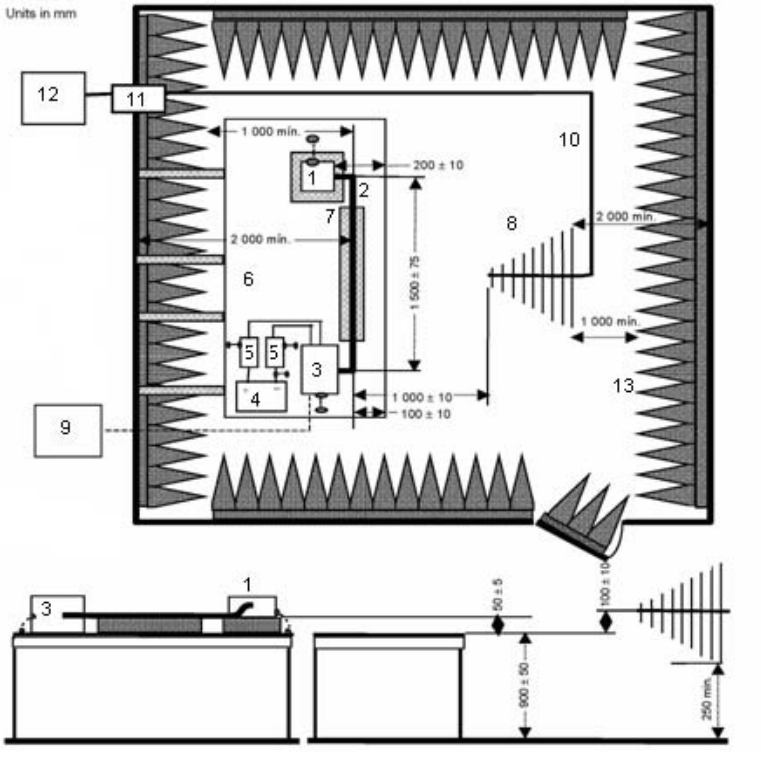
Radiated Susceptibility Test According to ISO 11452-2

The before mentioned ISO 11452-2 describes a possible method for the radiated immunity test accepted by the EMC directive (2004/104/EC EMC, 2004) for the fulfilment of electromagnetic immunity requirements of electric and electronic components on a vehicle.

Following the standard, the electromagnetic susceptibility (EMS) test must be done in a semi-anechoic chamber. The electromagnetic field is generated by an antenna connected to a RF amplifier. To monitor the electric field intensity level (V/m) inside the semianechoic chamber, an isotropic probe must be used.

Figure 2 shows the setup as explained in the standard for the radiated test on a vehicle device

Figure 2. Setup of the radiated susceptibility test



1. EUT (Equipment Under Test)
2. Test harness.
3. Load simulator.
4. Power supply.
5. Artificial network (AN de 50 Ω)
6. Ground plane (bonded to shielded enclosure).
7. Low relative permittivity support ($\varepsilon_r \leq 1.4$)
8. Antenna.
9. Stimulation and monitoring system.
10. High quality double-shielded coaxial cable (50 Ω)
11. Bulkhead connector.
12. RF signal generator and amplifier.
13. RF absorber material.

(equipment under test [EUT]). A metallic (copper or galvanised steel) ground plane of a minimum of 0.5 mm thickness and 1000 x 2000 mm (WxL) area has to be located 900±100 mm above the floor.

Each one of the power supply cables must be connected to the EUT through an artificial network (AN) [5] of 5 μH/50 Ω to get a reference impedance (usually 50 Ω). The ANs should be placed over the ground plane and connected to it.

The electric or electronic equipment under test has to be placed on a dielectric material [7] of low permeability ($\varepsilon_r \leq 1.4$) and 50±5 mm thickness. One of the EUT faces has to be placed 200±10 mm from the edge of the ground plane. The cables connected to the EUT are exposed along 1500±75 mm to the electromagnetic radiation generated by the antenna. They are placed on the same dielectric material as the EUT 100±10 mm away from the edge of the ground plane.

The antenna that generates the electric field has to be located at a 100±10 mm height above the ground plane, that is 1000 mm above the floor and also 1000 ± 10 mm away from the EUT cables.

The test procedure can be divided in two steps:

- A first one where the electric field level calibration is done (without EUT, cables nor ANs).
- A second in which the test is taken place based on the levels obtained in the preceding step.

In the calibration stage, an isotropic probe 150 ± 10 mm above the ground plane and 100 ± 10 mm away from the edge is used. The calibration is done for both horizontal and vertical electric field.

Aspects of Bluetooth Devices that are not Considered in Directive 2004/104/EC

Having mentioned some of the properties of Bluetooth, as well as the EMC regulation applicable to the automobile context, and focusing the study on the assessment of the susceptibility of the electrical and electronic components on board to radiations from different wireless devices, the following observations remain to be made:

- The specifications of the radiated susceptibility test, mentioned in the directive using the semianechoic chamber method to carry it out, determine that the range of frequencies to be tested is from 20 MHz to 2000 MHz. Therefore, the directive does not make it compulsory to test electrical and electronic automobile equipment at frequencies higher than 2 GHz. Bluetooth works at frequencies between 2.400 and 2.4835 GHz, and hence an electronic subsystem or component that complies with the directive does not guarantee electromagnetic compatibility in the presence of a Bluetooth device.
- The electrical field levels specified by the directive to be tested in the 20 to 2000 MHz range are of 30 V/m for 90% of the frequency band and 25 V/m for the whole frequency band. It is foreseeable that in the near future the directive will be modified to increase the range of frequencies to at least include the operating frequencies used by the wireless devices available on the market to automobile users.
- The test method specified in the directive corresponds to a situation in which the transmitter is not situated close to the equipment being studied. This leads to the use of a plane wave in the test setup, which requires one or more transmitter antenna working in far field. However, in this particular case it is easy to find Bluetooth transmitters within the automobile's own electrical and electronic system or another ones (introduced by users) operating a few centimetres away from the electronic systems and wires of the vehicle's electrical installation.

With this background, the present work is developed with the aim of determining whether a device that complies with the requirements of the EMC automobile directive presents any possible electromagnetic compatibility risks to Bluetooth transmitters located a short distance away. In addi-

tion a measure procedure is proposed for assessing the degree of interrelation between the electronics on board and the Bluetooth devices incorporated by vehicles' users.

Related Published Works

In the technical literature, negative examples of vehicle-communication system interaction can be found, as in the case of 'Project 54' (Kun, Lenharth, & Millar, 2004), in which the origin and possible solutions to random signal reception by appliances normally used by traffic police officers are analysed. There are other more complex cases, such as the one stated by Tatoian (2005), in which the possibility of equipping the police with electromagnetic systems in order to block cars in conflictive traffic conditions is assessed. The impact of the transient surrounding perturbations (especially due to electromagnetic interferences) on the dependability of systems distributed on TDMA-based networks in automotive domain is analysed in by Campos et al. (2002).

All of this justifies the interest of automobile manufacturers in regulating the incorporation of new information and communication technologies. In Australia for example, exists the FCAI (1997) initiative, in which the automobile industry and the nation's government are working together to establish the emission and susceptibility limits to which new vehicles must conform in order to guarantee the compatibility of the electronics on board the vehicle with the multimedia equipment for drivers available on the market. EMC centres work along the same lines in association with automobile manufacturers such as Audi or Renault (Renault, 2006).

On the other hand, there are several previous research works related to this subject. Stadtler Schoof, and Haseborg (2002) calculate that a 100 mW Bluetooth transmitter in far-field (1 m) generates a electric-field level of 2.45 V/m, that means a quite lower level to the one used in EMC test according to the 2004/104/EC standard. Nevertheless, simulations results presented by Schoof, Stadtler, and Haseborg (2003) inside a cockpit vehicle with a 100 mW Bluetooth transmitter achieved electrical-field levels of 25 V/m, which is close to the limit level indicated by EMC standard.

PROPOSED METHOD FOR ASSESSING THE POSSIBLE EFFECTS OF BLUETOOTH DEVICES USED INSIDE VEHICLES

Taking into account previous published studies (Schoof et al., 2003; Stadtler et al., 2002) and the EMC specifications in the automotive context, certain questions must be made in relation with the incorporation of Bluetooth transmitters in automobiles by either the manufacturer or the users of the vehicle. As mentioned earlier, the EMC directive (2004/104/EC EMC, 2004) does not require radiated susceptibility tests above 2 GHz and restricts the field level of the equipment under test to 25 or 30 V/m. Moreover, in present day traffic conditions, it is easy to find several Bluetooth transmitters inside the cabin of the vehicle and within a few centimetres of the vehicle's cables and electronic systems.

Fundament of the Proposed Measure

The setup for the radiated susceptibility test for an automobile component in accordance with ISO regulation 11452-2 (ISO 11452-2, 2004) was represented in the previously in the chapter. This setup contains similarities to the actual layout of the components inside a vehicle. For example, the equipment under test [1], wiring [2], simulators [3], and power supply [4], are placed on a ground plane that emulates the chassis of the vehicle. The length of wire exposed to the radiation is 1.5 m, being the usual length of cable on board a vehicle.

In this context, a study is made of the radio frequency current that is induced in the cable [2] when it is submitted to the action of a Bluetooth transmitter in near field, that is to say with a few centimetres between transmitter and cable.

Once the current induced in the EUT cable by the Bluetooth transmitter has been determined, the electrical field level that must be applied during

the radiated susceptibility test in order to induce a current value identical to that induced by the Bluetooth transmitter a few centimetres away is analysed. If the electric field level required to induce the current value is under the 25 or 30V/m specified by 2004/104/EC EMC, it will confirm that all equipment that fulfil the EMC directive should not present compatibility problems. However, if the electric field level is similar to or higher than the one specified by EMC directive, there is no guarantee that the automotive component will not have electromagnetic compatibility problems in close proximity to a Bluetooth transmitter.

PRACTICAL IMPLEMENTATION AND RESULTS

Following the guidelines indicated by Stadtler et al. (2002), the setup shown in Figure 3 is used for the present research work. The impedance presented by the EUT [1] between the cable and the ground plane [6] is modelled as an ideal impedance of 50 Ω. At the other end of the cable an ideal impedance of 50 Ω represents the one corresponding to the artificial network [5] or to other auxiliary equipment.

In the first approach at validating the proposed thesis the electromagnetic simulation tool FEKO (2005) is used. In the laboratory experimental phase, a R&S ESIB 26 spectrum analyser syntonised to the transmission frequency of the device is used to measure the induced current. The resistance of 50 Ω that corresponds to the EUT is provided by the spectrum analyser input; as an impedance of 50 Ω at the other end of the cable, a load 50 Ω with an N connector is used. The analyser will register the voltage value at its input terminals and by direct relation the value of current induced in the cable is determined.

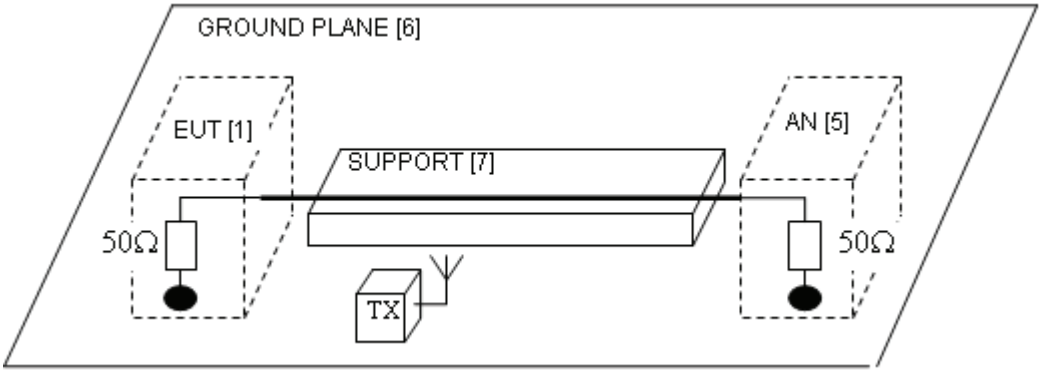
Design of the Interference Pattern

An electromagnetic radiation source in the 2.400 to 2.483 GHz range has been designed with adjustable power between 1 and 100 mW, emulating the behaviour of class I, II, and III Bluetooth transmitters. The radiation source consists of an antenna connected to a R&S SMR20 RF generator. The antenna design is based on a commercial radio frequency module (SparkFun, 2005), simulated using FEKO and implemented on a PCB.

Elements of the Setup

Figure 4 shows the setup used to measure the current induced in the cable when the Bluetooth transmitter is situated a short distance away. The right hand side of the cable is loaded with an impedance of 50 Ω, while the impedance of 50 Ω on the left hand side is provided by the spectrum analyser input (R&S ESIB 26), which is outside

Figure 3. Setup diagram of the test used to determine the current induced by a transmitter in near field

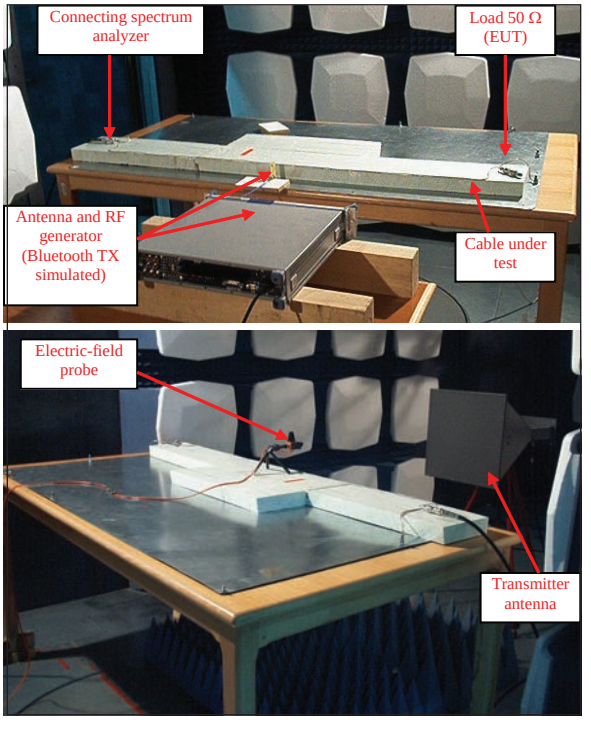


the semianechoic chamber (Space Saver of ETS) during the test and is connected by means of an RG214 cable. The attenuation caused by the RG214 cable is corrected by the spectrum analyser.

To measure the induced current, the radiation source is placed in different positions with respect to the 1.5 m long cable. The measurements are made with the transmitter facing the cable and in various positions along its length. The transmitter is placed at distances of 2 cm, 5 cm, and 8 cm from the cable and at heights with respect to the ground plane of 0.6 cm and 3.7 cm.

To determine the value of the electric field intensity (V/m), the setup represented in Figure 4 is used, corresponding to the radiated susceptibility test for automobile components (2004/104/EC EMC, 2004). The electric field level is registered by means of an isotropic electric-field probe (FP6001 AR) placed at a height of 10 cm above the ground plane and 10 cm from the edge facing the antenna. The value of the current induced by the radiation of the AT4000 AR antenna situated at a distance of 1 m is constantly measured on the spectrum analyser. The power transferred to the antenna is varied until the induced current values are identical to those obtained when the Bluetooth transmitter was situated a few centimetres from the same cable. This is the way to determine the electric field level that induces the same current as a Bluetooth transmitter in the conditions previously described.

Figure 4. Setup of the test used to measure the current induced by a transmitter in near field (top). Setup used to determine the electric field level (down)



Results

In the following section, some of the results about the setups proposed in previous sections obtained by both simulations and practical measurements made in the laboratory are given, with the principal aim of determining the electromagnetic compatibility risks caused by commercial Bluetooth transmitters in automobiles.

The FEKO tool is used to simulate a ground plane with a 150 cm cable above it at a height of 5 cm, with both ends loaded with a resistance of 50 Ω. A monopole antenna connected to a generator was used as a transmitter in the simulation. The simulations are made with the antenna transmitter situated in the centre of the 1.5 m cable structure and at distances of 2 cm, 5 cm, and 8 cm and at heights above the ground plane of 0.6 cm and 3.7 cm. In addition, the simulations are carried out taking into account the different power types (I, II, and III) specified by the Bluetooth technology.

Tables 1 and 2 represent a comparison between the results obtained with the FEKO simulation tool and those obtained in laboratory tests. First of all, the results belong to a transmitter working at 2.425 GHz and at a height above the ground plane of 0.6 cm are presented. The table shows the variation in the induced current as a function of the distance that separates the transmitter from the cable, and for three different power transmission (+20, +4, and 0 dBm). For example, in case the class I transmitter is separated a distance of 2 cm from the cable, the simulated current value

is 1990 μA in contrast with the value of 1870 μA experimentally obtained.

Besides, one can see in Table 2 the comparison between simulated and experimental induced current when the emission frequency is changed for three Bluetooth devices (class I, II, and III) at a distance of 5 cm and a height of 0.6 cm.

On the other hand, Table 3 shows some of the measurements obtained in the laboratory corresponding to the current induced by the transmitter located at a distance of 2 cm and 5 cm from the cable, and at a height above the ground plane of 0.6 cm. The same table shows the increase in the induced current due to the effect of different power class transmitter (class I, II, and III).

To conclude, Figure 5 shows the electric field levels that the structure being tested is submitted to in order to induce the same RF currents as those produced if a Bluetooth transmitter is situated in near field. The setup used for the test is the one

Table 1. Values obtained by simulation and experimentally of the induced current as a function of the transmitter distance. (frequency 2425 MHz and height 0.6 cm)

Wire Induced Current			
Power transmission Bluetooth devices	Distance (cm)	Simulation (μA)	Measurement (μA)
+20 dBm (Class I)	2	1990	1870.0
	5	879	715.3
	8	337	378.0
+ 4 dBm (Class II)	2	315	319.5
	5	139	123.0
	8	53.3	62.2
0 dBm (Class III)	2	200	203.4
	5	87.7	78.8
	8	33.5	43.3

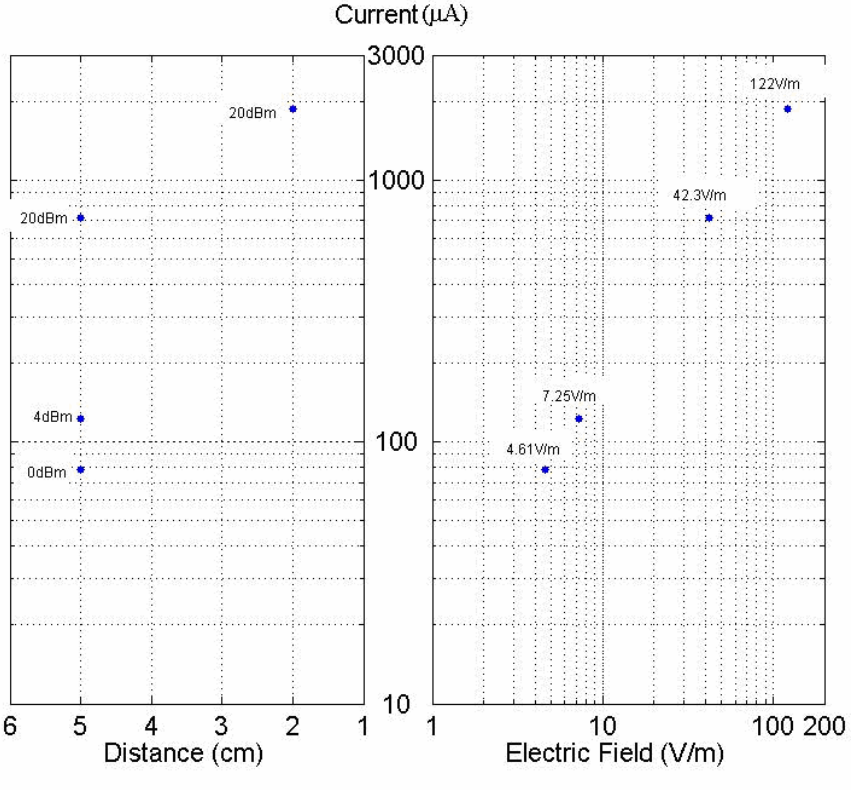
Table 2. Values obtained by simulation and experimentally of the induced current as a function of the transmitter frequency (distance 5 cm and height 0.6 cm)

Induced Current			
Power transmission Bluetooth devices	Frequency (MHz)	Simulation (μA)	Measurement (μA)
+20 dBm (Class I)	2400	921	827.0
	2425	879	715.3
	2450	941	604.0
	2475	1060	645.0
+ 4 dBm (Class II)	2400	145	142.8
	2425	139	123.0
	2450	148	104.8
	2475	167	111.7
0 dBm (Class III)	2400	91.1	90.8
	2425	87.7	78.8
	2450	93.8	67.5
	2475	105	71.28

Table 3. Measurement of the induced current as a function of the frequency and of the Bluetooth transmitter location (height 0.6 cm)

Measurement of induced current			
Power transmission Bluetooth devices	Frequency (MHz)	Distance 2 cm (μA)	Distance 5 cm (μA)
+20 dBm (Class I)	2400	1974	827.0
	2425	1870	715.3
	2450	1772	604.0
	2475	1862	645.0
+ 4 dBm (Class II)	2400	335.7	142.8
	2425	319.5	123.0
	2450	301.6	104.8
	2475	331.5	111.7
0 dBm (Class III)	2400	213.3	90.8
	2425	203.5	78.8
	2450	193.0	67.5
	2475	203.0	71.28

Figure 5. Identical induced current on the cable under test by the intensity of electric field (V/m) according to the described test as well as Bluetooth transmitters working with variable distance and power (dBm)



shown in Figure 4 (down). For example, a class I transmitter (+20 dBm) located at a distance of 5 cm and at a height of 0.6 cm induces a current of 715 μA. In the same way, this transmitter situated at a distance of 2 cm induces a current of 1870 μA. Identical current values are induced when the wire loaded by resistances of 50 Ω is exposed to a uniform plane wave with an electric field level of 42.3 V/m and 122 V/m, respectively.

FUTURE WORKS

Once the above shown results are analyzed, the authors suggest to keep on evaluating the electromagnetic field generated from these kinds of wireless communication devices and others alike, varying the setup conditions (relative cable and antenna location, cables, different antennas transmitting simultaneously, etc.). All this is done comparing the results obtained from the simulation tools as well as from the experimental tests in the EMC laboratory.

It would also be interesting to study and evaluate the amplifying effect due to the metallic structure of the cabin, measuring inside and outside the vehicle.

CONCLUSION

From the simulated and experimental results obtained by this work, it can be deduced that the electromagnetic interference supported by the cable structure under study, when situated a few centimetres from a commercial Bluetooth transmitter, is similar to the action of a plane wave with electric field levels superior to those specified by directive 2004/104/EC (25 or 30 V/m).

Comparing the magnitude of the electric fields obtained in the present analysis with the real values at which on board electronic components are tested in accordance with the EMC directive, it can be deduced that Bluetooth transmitters of 20 dBm can cause electromagnetic susceptibility problems in the vehicle's electronic and electrical systems, which would not be detected during the radiated susceptibility test according to a valid EMC directive for automobiles.

In short, more consideration should be given to the electromagnetic interference generated by Bluetooth devices as they get closer to electrical and electronic circuits whose performance they can affect, and even more so in confined spaces where multiple sources of interference coexist, as is the situation with automobiles. The effect of increasing the power of the transmitter or reducing the distance between it and the wired elements of the automobile is equivalent to submitting them to increasing electric far-field levels in radiated susceptibility tests in accordance with the 2004/104/EC EMC directive, which increases the risk of a failure in the system.

This work leads to support the need for the prevailing EMC directive to be modified in order to assess and ensure the electromagnetic compatibility of automobiles' on board systems in the presence of wireless devices with a frequency range above 2.0 GHz.

ACKNOWLEDGMENT

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KEY TERMS

Anechoic (Semianechoic) Chamber: An anechoic chamber is a room in which there are no echoes. This description was originally used in the context of acoustic (sound) echoes caused by reflections from the internal surfaces of the room but more recently the same description has been adopted for the radio frequency (RF) anechoic chamber. A RF anechoic chamber is designed to suppress the electromagnetic wave analogy of echoes: reflected electromagnetic waves, again from the internal surfaces. Both types of chamber are usually built, not only with echo suppression features, but also with effective isolation from the acoustic or RF noise present in the external environment. In a well designed acoustic or RF anechoic chamber the equipment under test will only receive signals (whether acoustic or RF) which are emitted directly from the signal source, and not reflected from another part of the chamber. The semianechoic chamber is a shielded room with radio frequency absorbing material on the walls and ceiling (not on the ground). This semi-anechoic chamber simulates an open field test site, and eliminates any ambient signals that may be present in an open field environment.

Bluetooth (Class I, II, and III): Bluetooth is the name of a wireless technology standard for connecting devices, set to replace cables. It uses radio frequencies in the 2.45 GHz range to transmit information over short distances of generally 33 feet (10 meters) or less. By embedding a Bluetooth chip and receiver into products, cables that would normally carry the signal can be eliminated.

There are currently three flavours or classifications of Bluetooth devices, relative to transmitting range. As the range is increased the signal used in the respective classification is also stronger. Note that class III devices are comparatively rare.

Class	Signal Strength	Range
Class I	100 mW (+20dBm)	Up to 328 feet (100 meters)
Class II	2.5 mW (+4 dBm)	Up to 33 feet (10 meters)
Class III	1 mw (0 dBm)	Up to 33 feet (10 meters)

CISPR: The Special International Committee on Radio Interference(abbreviated CISPR from the French name of the organization, Comitéinternational spécial des perturbations radioélectriques) is concerned withdeveloping norms for detecting, measuring and comparing electromagneticinterference in electric devices. CISPR's principal task is at the higherend of the frequency range, from 9 kHz upwards, repairing standards thatoffer protection of radio reception from interference sources such aselectrical appliances of all types, the electricity supply system,industrial, scientific and electro-medical RF, broadcasting receivers (soundand TV) and, increasingly, information technology equipment (ITE).

EMC-EMI-EMS: EMC is an abbreviation for electromagnetic compatibility. This means interoperability, or an electronic device's ability to operate in an electric environment without interfering other electronic devices (emission), and without being interfered by other devices in its vicinity (immunity).EMC is divided into two main areas: electromagnetic interference (EMI) and electromagnetic susceptibility (EMS). These two areas are again divided into two categories of phenomena: conducted phenomena and radiated phenomena. EMC testing comprises measurements of the emission generated on in- and outgoing cables, the emission generated as electric fields surrounding the device, immunity against several disturbance phenomena on in- and outgoing cables, immunity against electric fields generated by other electronic devices and radio transmitters, and immunity against electrostatic discharges generated by human intervention.

Near Field Communication (NFC): A short-range wireless connectivity standard (Ecma-340, ISO/IEC 18092) that uses magnetic field induction to enable communication between devices when they are touched together, or brought within a few centimetres of each other. Jointly developed by Philips and Sony, the standard specifies a way for the devices to establish a peer-to-peer (P2P) network to exchange data. After the P2P network has been configured, another wireless communica-

tion technology, such as Bluetooth or Wi-Fi, can be used for longer range communication or for transferring larger amounts of data.

RF: Short for radio frequency, any frequency within the electromagnetic spectrum associated with radio wave propagation. When a RF current is supplied to an antenna, an electromagnetic field is created that then is able to propagate through space. Many wireless technologies are based on RF field propagation, including cordless phones, radar, ham radio, GPS, and radio and television broadcasts. RF waves propagate at the speed of light, or 186,000 miles per second (300,000 km/s). Their frequencies however are slower than those of visible light, making RF waves invisible to the human eye.

WLAN: The acronym for wireless local-area network. Also referred to as LAWN. A type of local-area network that uses high-frequency radio waves rather than wires to communicate between nodes. LAN is a computer network that spans a relatively small area. Most LANs are confined to a single building or group of buildings. However, one LAN can be connected to other LANs over any distance via telephone lines and radio waves. A system of LANs connected in this way is called a wide-area network (WAN).

Chapter XLIII
Security in WLAN

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ABSTRACT

The great promise of wireless LAN will never be realized unless there is an appropriate security level. From this point of view, various security protocols have been proposed to handle wireless local-area network (WLAN) security problems that are mostly due to the lack of physical protection in WLAN or because of the transmission on the radio link. The purpose of this chapter is (1) to provide the reader with a sample background in WLAN technologies and standards, (2) to give the reader a solid grounding in common security concepts and technologies, and (3) to identify the threats and vulnerabilities of WLAN communications.

WLAN STANDARDS AND TECHNOLOGIES, BENEFITS AND USE CASES

IEEE 802.11/wireless local-area network (WLAN) technologies (WLAN, 2003) have evolved phenomenally over the last few years. They have been widely deployed in a variety of network environments and they properly converge with actual Internet and 3G infrastructures.

IEEE 802.11 refers to a set of specifications for WLAN developed by IEEE. It specifies an over-the-air interface between a mobile station (STA) and a base station as well as between two mobile stations. Basically, WLAN networks can be seen as extensions of wired Ethernet networks. WLAN leverages on a set of newest digital communications technologies to make it possible to establish a local area network for computer communications without the use of cables.

IEEE approved the first 802.11 standard in 1997. This version is limited to only 1 and 2 Mbps data rates. Subsequently in 1999, 802.11a and 802.11b were approved, expanding to new radio bands (changing the usage of the 2.4 GHz ISM band and adding usage of the 5 GHz UNII band) and increasing the available data rates to 54 Mbps and 11 Mbps, respectively. Consequently, large deployments of

802.11 WLAN started being rolled out, especially in enterprises to replace or extend the wired local-area network (LAN) with an implementation of WLAN, and in airports and various business venues where they installed several WLAN access points offering a public Internet access (so-called hotspots), which can range from a small covered zone to many square miles of overlapping hotspots in metropolitan areas.

While the most obvious advantage of the WLAN is mobility, there are also other benefits:

- **Installing and maintaining flexibility:** Installation of a WLAN system is fast and easy and eliminates the terminal cabling costs. It extends to area where wires cannot be installed.
- **Apparent ease of use:** WLAN is easy for novice and expert users alike, eliminating the need of a large knowledge to take advantage of WLAN.
- **Transparency:** WLAN is transparent to a user network, allowing applications to work in the same way as they do in wired LANs.
- **Scalability:** WLANs are designed to be simple or complex; they range from networks suitable for a small number of nodes to full infrastructure networks of thousands of nodes and large physical area by adding access points to extend coverage and to provide users with roaming between different areas.

WLAN was developed to extend wired LAN wirelessly and therefore to minimize Ethernet cabling. It was designed to provide "data obscurity" equivalent to that provided by wired Ethernet with easier installation. However, there is some difference between WLAN and wired LAN due to constraints introduced by the first, especially the shared medium, interference, the collisions that cannot be detected reliably, the physical boundary that is difficult to control, and to the signal. These differences make the WLAN security harder to maintain in comparison to wired LAN. In WLAN, it is possible for an attacker to snoop on confidentiality communications or modify them to gain access to the network much more easily than the wired LAN. The open access to the networks permits malicious action at a distance and simplify passive interception. The temptation for unauthorized access and eavesdropping is also a reality (Khan & Khwaja, 2003) because an attacker could easily access the transport medium. This is not easy in wired LAN due to the physical access to the media. WLANs have introduced a new security threat, sometime referred to as parking lot attack (Arbaugh, 2003) (i.e., a person with a wireless computer and a makeshift antenna can gain access to your the WLAN from hundreds of feet away). Other security issues are mostly because of the lack of physical protection of the wireless network access or of the transmission on the radio that cannot be confined to the walls of an organization.

The original 802.11 standard defines authentication and encryption mechanisms based on the use of the wired equivalent privacy (WEP) protocol. Unfortunately, this protocol suffers from serious design flaws (Miller & Hamilton, 2002). Furthermore, it does not define a key management mechanism; it presumes that the secret key is conveyed between WLAN entities through a secure channel independent of 802.11 WLAN. As a result of different flaws discovered in WEP, the security of WLAN has been widely studied, and a set of standards have been developed by IEEE and IETF, especially 802.1X (802.1X, 2004), 802.11i (802.11i, 2004) and extensible authentication protocol (EAP) (Aboba, Blunk, Vollbrecht, Carlson, & Levkowetz, 2004). The 802.1X standard has been standardized by 802.1 working group. 802.1X was initially conceived to securely manage the access to different IEEE 802.1 networks. It is a framework for authenticating and controlling user traffic at the network level, as well as dynamically varying and exchanging encryption keys between a mobile station and an authentication server. By pushing the authentication method to the virtual layer, the 802.1X defines an open security architecture, which principally allows user authentication and, optionally, session key generation and derivation on a per-user and per-session basis. Because of this possibility for dynamic provisioning, 802.1X is used as the common base in the current WLAN

security suites such as Wi-Fi protected access (WPA) (WPA, 2003) and IEEE 802.11i (802.11i, 2004).

The rest of the chapter presents a more detailed description of the various WLAN standards from the security perspective: challenges and possible attacks in WLAN security; WLAN infrastructure security; authentication, authorization, and access control; confidentiality and privacy; and key management and establishment.

WLAN MANAGEMENT FRAMES

A WLAN network is formed by entities called stations (STA). A WLAN can operate in two modes: infrastructure and ad hoc. In the ad hoc mode, each STA communicates directly with other stations. In the infrastructure mode, stations communicate with each other via a special STA, called access point (AP). Each AP additionally has a connection to the distributing system (DS), which can take different forms (wireless, wired, OSI layer, etc.). In this chapter, we focus on the infrastructure mode.

The infrastructure mode extends the range of the wired LAN. It introduces a notion of basic service set (BSS). Each BSS is formed by an AP and associated stations, and can be roughly understood as a WLAN equivalent of a cell (a base station and mobile nodes). It is uniquely identified by the medium access control (MAC) address of the STA of its AP, called BSSID. By using their DS connection, several APs can allow a station to move from one BSS to another. Several BSSs may be collected, constructing an extended service set (ESS). The identifier of the ESS is a case sensitive string of 32 bytes (ESSID), and can be roughly understood as a "network name." In the infrastructure mode, it is usually called SSID for convenience.

One of the primary services of WLAN management frames is to provide access control reliability. This is done originally based on a predetermined set of MAC address and improved later with 802.1X. The access control usually implements a way to provide authentication or authorization to a terminal attached to the network. WLAN uses a concept called port-based access control that is based on the notion of a port. The port-based access control blocks all traffic on a (logical) port until some condition is true. The condition for the port opening is a successful user association and authentication.

An association precedes each communication between the STA and the AP. The association is formed between a STA and an AP by exchanging messages, by the means of so-called management frames, allowing both STA and AP to create and to maintain the association states. WLAN defines three states: unauthenticated and unassociated, authenticated and unassociated, and authenticated and associated.

The management frames can be started by the STA sending a probe request management frame to find an AP affiliated with a selected ESSID, or scanning the beacon management frame broadcast by the APs at a fixed interval. As part of the association processes, the STA and the access point perform an authentication. IEEE 802.11 originally defines two authentication modes, the open system authentication (OSA), practically equivalent to no authentication, and shared key authentication (SKA), a simple challenge handshake protocol based on a preshared key between the STA and the AP and the specified WEP protocol. Furthermore, other methods can be used to restrict the access to an AP, such as classical MAC address filtering (whitelisting or blacklisting STA MAC addresses) and the suppression of service advertisement, usually called SSID hiding.

It must be noted that neither of these methods can be considered sufficiently secure given the current usage of the 802.11 technology. Since MAC addresses need to be transported in clear and can be easily changed, the MAC address filtering is not enough of a barrier. SSID hiding only can work as long as nobody uses the service, since the associating STA will try to solicit an AP under a given SSID, thus effectively disclosing this "secret." The included SKA scheme lacks mutuality and is way too static (no session key derivation, no key management) to be applicable in an operational industrial environment. Accidentally SKA was

found to be misconceived, effectively rendering it useless. The details of these findings will be discussed in the next sections.

WLAN SECURITY ESSENTIALS

The 802.11 standard defines an optional encryption scheme to protected data streams exchanged over-the-air between the STA and the AP. This scheme, called WEP, was designed to prevent unauthorized access to the wireless LAN traffic. It uses the stream cipher RC4 for confidentiality equivalent to a traditional wired network, and a CRC-32 checksum for integrity protection. Shared key authentication type requires WEP support.

The 802.11 standard does not define how to distribute shared keys to the equipment in the network. In other words, WEP key management and distribution is outside the scope of 802.11.

WEP-Based Authentication

The first feature of WEP is to prevent unauthenticated users from gaining access to the WLAN network. STA attempting to gain access to the network must send an authentication frame containing, among others, its asserted identity to the AP, which replies with another authentication frame transporting a challenge text. The device encrypts the challenge text using WEP with the shared key and its own initialization vector (IV), concatenates the encrypted output to the IV, and sends the result to the AP:

STA→AP: Authentication Request (STA asserted identity)
AP→STA: Challenge
STA→AP: WEP(Challenge, IV, Key) = Challenge XOR RC4(IV | Key)
AP→STA: Success <or> Reject.

Using the same key, the AP decrypts the response and verifies that the decrypted text matches the challenge text it sent to the device, before accepting or denying device access to the network.

WEP Confidentiality and Data Integrity

WEP uses a 40-bit key that is concatenated to a 24-bit IV to form the traffic key. The resulting key is used as an input to the RC4 pseudo-random number generator (PRNG) to generate a pseudo-random key sequence.

When a device encrypts data using WEP, it calculates the integrity check value (ICV) over the data to be sent (ICV is implemented as a CRC-32-bits). The device concatenates the data and the ICV before the result is XORed with the key sequence (in a typical stream cipher manner).

Upon reception, the AP retrieves the IV from the arrived packet to generate the same pseudo-random key sequence. Then, the AP XORs the key sequence to the received frames and computes the ICV of the decrypted text, comparing it to the ICV of the received packet. If the two ICV do not match, the AP sends an error indication to the sender.

Note that due to interference, out-of-order or lost-packet rates are plausible within 802.11 communication channels. Therefore and in order to ensure the so-called self-synchronisation property, WEP uses a per-packet RC4 key and generates a separate keystream per packet. For that, WEP concatenates a per-packet IV to the WEP key.

ISSUES IN WLAN SECURITY

Due to the shared nature of the wireless medium, it is easy to create associations with unprotected wireless networks. Consequently, unauthorized STAs are able to launch attacks on a wireless network, for example, to affect the WLAN performance or to get an Internet access, as well as on another STA to eavesdrop on its established association. Attacks are classified as active and passive.

A passive attack is an attack where an unauthorized attacker monitors or listens on the communication between two or more parties. Active attacks have the possibility of inflicting undetected corruption on the data in transit by manipulating the cipher text in special ways that do not change its built-in cyclic redundancy checks.

WLAN devices broadcast their MAC addresses over-the-air and it is therefore easy to observe the MAC address for an associated mobile station and spoof it to masquerade as a legitimate device.

Due to the nature of WLAN, intruders can flood the open medium access and are able to execute denial-of-service attacks (DoS) to bring down WLAN access or services. An attacker may launch denial-of-service attacks by spoofing, replaying, or generating management frame packets.

Another problem related to the open medium is jamming WLAN frequencies. Jamming against WLAN is almost impossible to prevent and can be executed easily as noise or interference on channels that deliver WLAN services. For example, in a military environment, jammers are often located in helicopters as the line-of-sight propagation gives them an advantage over communication transmitters located on the ground (Stahlberg, 2000).

WLANs are also vulnerable to session hijacking attacks due to the lack of authentication of the management frames as well as to the WLAN state machines. Session hijacking is a combination of DoS and identity spoofing attacks and it can be launched by 1) eavesdropping on the medium to discover the MAC address of a legitimate station and/or of the AP, 2) deauthenticating the legitimate station to terminate its connection to the AP (spoofing STA or spoofing AP addresses), and 3) using the eavesdropped MAC to reauthenticate to a different or to the same AP on the same WLAN.

WEP Weaknesses

Shared key authentication was designed to help in reducing attacker activities against WLAN. Unfortunately, WEP has turned out to be much less secure than intended. Fluhrer, Mantin, and Shamir's (2001) paper entitled "Weaknesses in the Key Scheduling Algorithm of RC4" describes how an attacker can intercept transmissions and gain unauthorized access to wireless networks. Other problems are related to the insufficient IV length (thus permitting to decrypt frames without key knowledge), absent key management (on the one hand resulting in manual settings and typically weaker alphanumeric keys, and on the other hand directly exposing the long term secret), and to the absent message integrity checking (the available CRC32 integrity does not depend upon the keys and mainly targets transmission problems; it is therefore possible to alter a packet whose content was known even if it had not been decrypted). More information on WEP attacks may be found by Borisov, Goldberg, and Wagner (2001).

In a WLAN context, a passive attack takes advantage of several weaknesses in the key-scheduling algorithm of RC4. It could be done also by a comparison of the encrypted version of a known message (e.g., TCP fields) to repetitive IV-based encryption combinations of the known text and to reveal the secret key (Morrison, 2002). In fact, the 24-bit IV implies that 2^{24} packets can be protected with the same key, before changing the key. Because the IV is relatively short, and is transmitted in the clear text, it will be repeated with sufficient frequency that the rest of cipher can be relatively easily cracked. On the other hand, WEP by its design cannot efficiently reduce overhead of denial-of-service attacks. In particular, it does not protect beacon packets, or the part of the packet header, which includes the MAC address unencrypted. Consequently, it is not hard to infiltrate the WLAN using WEP.

Consequently, a dedicated task group called 802.11i has been set up by IEEE to create a replacement security solution. The released IEEE 802.11i amendment introduces an improved security mechanism called Wi-Fi protected access (WPA) to solve WEP-related authentication and confidentiality problems and to introduce an efficient frame integrity scheme. 802.11i security solution (called robust secure network or WPA2) uses a new counter-mode/CBC-MAC protocol (CCMP) cipher based on the advanced encryption standard (AES) instead of RC4.

802.1X, WPA, AND IEEE 802.11I (WPA2)

IEEE 802.11i is a dedicated task group to specify and to create a replacement security solution. It provides enhanced security services and mecha-

nisms for the IEEE 802.11 medium access control beyond the features and capabilities provided by WEP. These security services are established by defining temporal key integrity protocol (TKIP) and counter-mode/CBC-MAC protocol (CCMP) that provide more robust data protection mechanisms than what WEP affords. 802.11i also introduces the concept of a security association and defines security association management protocols called the 4-way handshake and the group key handshake. Also, it specifies how IEEE 802.1X may be utilized by IEEE 802.11 LANs to effect authentication.

The IEEE 802.11i architecture usually contains or implements the following components:

- 802.1X for authentication, entailing the use of IETF's EAP and an authentication server.
- Robust security network (RSN) for keeping track of associations.
- AES-based CCMP to provide confidentiality, integrity, and origin authentication. Another important element of the authentication process is the four-way handshake, explained below.

WPA

Because WEP has been shown to be totally insecure and in order to strengthen the weak keys used by WEP, 802.11 Working Group has proposed a new WPA protocol called TKIP. This protocol is designed to strengthen the security of 802.1X networks and to leverage the existing WEP-enabled WLAN network interface card (NIC), while remaining backward compatible with existing hardware (no change in the hardware engine). This is done by distributing firmware/software upgrades including new algorithms to be added to WEP, such as message integrity code (MIC) and per-packet key mixing function.

TKIP uses a key scheme based on RC4, but unlike WEP that uses the master key for authentication and per-packet encryption, TKIP extends this key hierarchy to reduce the exposure of the master secret and to provide per-packet key mixing, a message integrity check as long as a rekeying mechanism. Consequently, TKIP ensures that every data packet is sent with its own unique encryption key. Moreover, it includes a key hash function to improve resistance against Fluhrer attacks (Fluhrer et al., 2001) and MIC and it uses 802.1X for key management and establishment. The MIC prevents forged packets from being accepted. Thanks to per-packet key mixing, it is very hard for an eavesdropper to correlate the IV and the per-packet key used to encrypt the packet (Chandra, 2005). More precisely, TKIP hashes the combination of the IV value, the data encryption key (derived from the master secret), and the MAC address. This mechanism addresses the WEP problem when concatenating the key with the IV to form the traffic key, and then reducing the ability of the related key attack.

Key Hierarchy

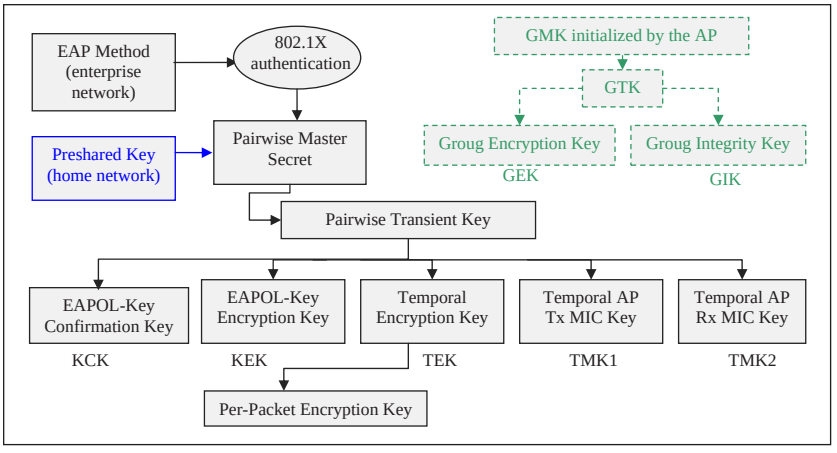
The master secret used in key hierarchy can be a preinstalled key or a per-session key. In fact, TKIP can be used with an IEEE 802.1X authentication server, which shares a master key with each user as a consequence of a successful authentication process as well as in a preshared key (PSK) mode where all authorized users share a PSK. These two modes target two distinct environments respectively, enterprise and home networking.

As we cited before, TKIP extends the WEP key hierarchy to reduce the exposure of the (long term) master secret and to provide per-packet key mixing, a message integrity check as long as a rekeying mechanism. This extension is shown in the following figure. At a given layer, the different keys are generated by applying the pseudo random function (PRF) on, among others parameters, the key of the upper layer and the MAC addresses of the two endpoints.

Preshared Key

As we cited before, 802.11i security solution uses 802.1X (see next section) that requires a logical authentication server entity. However, 802.11i defines the preshared key solution as an alternative to 802.1X-based master key establishment. This solution can be used for home or small networks

Figure 1. WPA Key hierarchy



and does not require installation of an authentication server.

The PSK is 64 hexadecimal digits or a pass phrase 8 to 63 bytes long, in which each STA has its own PSK tied to its MAC address and uses it to get access to the network. The key hierarchy is showed in Figure 1. The PSK is however used directly to compute the pair-wise transient key (PTK). The rest of the key computation process remains unchangeable.

The PSK is a 256-bit random value or a pass phrase 8 to 63 bytes long, in which each STA has a PSK tied to its MAC address and uses it to get access to the network. The key hierarchy is showed in Figure 1. The PSK is however used directly to compute the PTK. The rest of the key computation process remains unchanged.

IEEE 802.1X

IEEE 802.1X is introduced for port-based network access control. It provides authentication to stations attached to a LAN port, establishing a point-to-point connection in case of success or preventing access from that port if authentication fails.

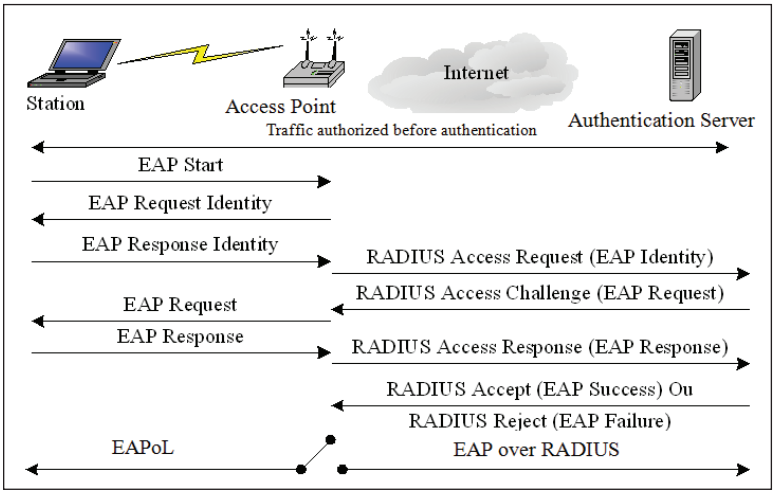
802.1X uses three terms:

- **The Supplicant:** A station that requests access to the network offered by the authenticator. It dialogue with the authentication server through the authenticator.
- **The Authenticator:** Typically a wireless access point that controls the state of each port (open/close) and mediates an authentication session between the supplicant and the authentication server.
- **The Authentication Server:** Typically a (remote authentication dial in user service) RADIUS server that performs the authentication process on behalf of the authenticator. The resulting decision consists of whether the supplicant is authorized to access the authenticator's network. Note that 802.1X does not require use of a central authentication server, and thus can be deployed with standalone bridges or access points, as well as in centrally managed scenario (802.1, 2004).

The most important component in 802.11i architecture is the IEEE 802.1X port access entity (PAE), which controls the forwarding of data to and from the MAC. A STA always implements a Supplicant PAE and implements EAP peer role, and an AP, acting as an Authenticator, always implements an Authenticator PAE and implements the EAP Authenticator role.

802.1X is based on EAP, which is a powerful umbrella that shelters multiple authentication

Figure 2. 802.1X messages exchange between a supplicant, an authenticator, and the authentication server



methods. When IEEE 802.1X authentication is used within 802.11 networks, EAP is used transparently between the station and the (usually remote) authentication server and relayed through the AP. 802.1X requires the cooperation between the authentication server and an EAP method. In the case of a wireless LAN, the EAP method is required to perform mutual authentication and key management and distribution \REF-RFC-REQ-EAP-WLAN. Using the flexibility proposed by the IEEE 802.1X architecture, multiple EAP-based security protocols and mechanisms such as EAP-SIM (Haverinen & Salowey, 2006), EAP-TLS (transport layer security) (Aboba & Simon, 1999), and protected-EAP (Palekar, Simon, Zorn, Salowey, Zhou, & Josefsson, 2004) are proposed. These EAP methods are used with the 802.11i (or WAP2) and WPA standards in order to establish authenticated access and key calculation and distribution.

IEEE 802.11i (WPA2)

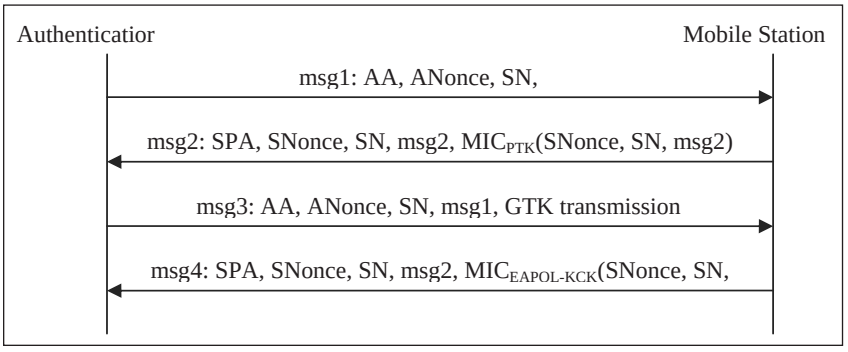
The procedures defined in 802.11i adopt the key-hierarchy defined by WPA and provide fresh keys by means of protocols called the 4-way handshake and group key handshake. 4-way handshake is a pair-wise key management protocol used to confirm the mutual possession of a pair-wise master key (PMK) by two parties and to distribute a group temporal key (GTK). Several keys are established as a result of a successful authentication. The keys are derived from the PMK (in particular, the pair-wise transient key).

802.11i defines two key hierarchies: (a) pair-wise key hierarchy to protect unicast traffic and (b) GTK, a hierarchy consisting of a single key to protect multicast and broadcast traffic. Furthermore, it defines TKIP (uses existing hardware) and CCMP (needs additional hardware) to repair the problems caused by WAP. TKIP provides stronger security through a keyed cryptographic message integrity code (MIC), an extended IV space, and a key mixing function. And the CCMP is used to provide data confidentiality, integrity, and replay protection.

4-Way Handshake

Once the authenticator and the mobile station have agreed upon a shared PMK, they can begin a 4-way handshake: STA represents the station; STAA and AA, SNonce and ANonce, represent the MAC address and the nonce of the station and authenticator, respectively; SN is the sequence number; msg1, msg2, msg3, and msg4 are indicators of different message types; and $MIC_{EAPOL\text{-}KCK()}$ represents the

Figure 3. 802.11i 4-way handshake



message integrity code calculated for the contents inside the bracket with the fresh PTK.

EAP

EAP is the IETF standard for extensible authentication for network access. It was designed to enable an extensible OSI layer 2 authentication before the IP configuration could be acquired. Originally developed for use with point-to-point protocol (PPP) (Simpson, 1994), it has subsequently also been applied to IEEE 802 wired networks (802.1, 2004) and wireless networks such as 802.11 (WPA, 2003).

EAP can be viewed as a transport framework and supports multiple authentications mechanisms such as EAP-TLS, EAP-SIM and EAP-AKA, without having to prenegotiate a particular one. Authenticators do not need to understand each request type and may be able to simply act as a pass-through agent for a "back-end" server on a host. The authenticator starts the EAP exchanges with a port closed state; it needs however to look for the success/failure sent by the authentication server to open/close the port.

EAP packets include all relevant information about the required authentication scheme, for example, authentication method and packet code (request, response, success, or failure), and allow for method negotiation (a special NAK type). The exact content of these packets is up to the chosen EAP authentication mechanism. The progression of an authentication procedure also depends on the chosen authentication mechanism.

Authentication Server

Typically, 802.1X performs authentication and key management through a server, such as AAA RADIUS (authentication, authorization and accounting, remote authentication dial in user service) or DIAMETER. RADIUS (Aboba, 2006; Rigney, Willens, Rubens, & Simpson, 2000) is a widely deployed AAA protocol. As we cited, the EAP packets are carried by EAPOL directly over the wireless interface between the STA and the access point, and by EAP over RADIUS between the access point and the authentication server. This effectively creates an EAP conversation channel between the station and the authentication server, which allows the supplicant to authenticate. The authentication is realized by the chosen authentication mechanism. This phase will also generate a secret key that will be used in the key hierarchy. The generated key of EAP between the STA and the AAA server is therefore conveyed to the AP using the AAA protocol.

EAP-TLS

EAP-TLS defines the transport of transport layer security (Dierks & Allen, 1999) in EAP. TLS is one of the most deployed security protocols, which is mainly due to its integration in navigators. TLS is an IETF-standardized authentication method derived from the secure sockets layer (SSL) protocol.

TLS authentication within EAP is quite straightforward. The TLS handshake packets are encapsulated in an appropriate EAP form and transported

between the station and the authentication server. Because of the size of the certificates exceeding typical link MTUs, EAP-TLS additionally defines fragmentation. When the TLS authentication dialog succeeds, the authenticator (host requiring the authentication on behalf of a supplicant) gets the authorization information delivered within the RADIUS access-accept message and access to the network is granted.

EAP-TLS defines the full Handshake phase that involves the exchange of X.509 certificates and the cryptographic information to allow peers to be authenticated. This step requires several operations. First, peers must verify the integrity of certificates and should generally support certificate revocation messages (the peer may not have Internet connexion and therefore it can use online certificate status protocol (OCSP) to obtain the revocation status of a certificate [Blake-Wilson et al., 2003]). Also, the certificate must be verified to ensure it is signed by a trusted certificate authority (CA). Finally, the client (i.e., station) should be able to view the information about the certificate and the CA root.

EAP-TLS indicates that a secure connection may be terminated and resumed later. This (abbreviated handshake) phase may be established if the client and the server agree. During this phase, the client and the server will use the master key, which is calculated during the last full handshake phase, to mutually authenticate and to calculate and generate new keys for the secure channel. After that, they verify the integrity of their exchanged handshake messages and then begin to exchange data over the secure connection.

The abbreviated handshake allows the client and the server to avoid several expensive cryptographic operations such as private key computations, client/server certificate decoding and verification, online consultation of certificate revocation list (CRL), and generation and encryption/decryption of the premaster secret key, which is used for generating the master secret key. Moreover, the abbreviated TLS handshake shortens the authentication delay and preserves the precious radio bandwidth.

Security Problems

802.1X is intended to provide strong authentication, as well as key management and distribution. However, 802.1X suffers from some security problems related to its use in conjunction with WLAN 802.11. This conjunction suffers from the absence of an ensured synchronization of the various state machines, causing potential attacks such as man in the middle, session hijacking, and DoS. Furthermore, others attacks are possible because EAP does not include any integrity information to its transported packets. For example, at the end of the authentication process, the authenticator will send an EAP notification message to indicate the success or the failure of that process. Since this notification does not include any integrity protection data, an attacker can easily replace an EAP failure with EAP success and deny the access to the WLAN network.

On the other hand, He and Mitchell (2004) demonstrate a DoS attack against a 4-way handshake of 802.11i. The attack can be realixed by impersonating the authenticator, composing a Message 1, and sending to the STA. The attacker sends a forged Message 1 to the STA after Message 2 of the 4-way handshake. The STA will calculate a new PTK corresponding to the nonces for the newly received Message 1, causing the subsequent handshakes to be blocked because this PTK is different from the one in the authenticator. The attacker can determine the appropriate time to send out Message 1 by monitoring the network traffic or just flooding Message 1 with some modest frequency.

Some available tools can be used to crack WAP in PSK mode, especially coWPAtty, which is a brute-force cracking tool, which means that it systematically attempts to crack the WPA-PSK by testing numerous passwords, in order, one at a time (Fogie, 2005).

Additional Security Needs: Privacy and Identity Protection

During the authentication and security association phases, almost all security protocols, including 802.1X and EAP methods, exchange identity

related data in clear text and without any encryption. Therefore, security parameters flowing in the network could potentially be logged, archived, and searched.

Basically, certificates are issued by a trusted third party linking the identity of the certificate owner to the public key, whereas the shared secret is managed through its identifier. Certificate or shared key identifiers are usually sent in clear text and consequently, entities cannot protect their identities from eavesdropping. Thus, an intruder can learn who is reaching the network, when, and from where, and hence, track users by correlating client identity to connection location. Especially in WLAN, where the access medium is open to eavesdroppers, and the mobility is a reasonable service, the location tracking can be a serious security issue. The PEAP and EAP-TTLS authentication methods can be used to protect user identity. Both are two-phase protocols with the first phase used to establish a TLS with only server authentication and the second phase used to deliver, among others, the user identity.

Privacy and identity protection are increasingly required for 802.1X/EAP and consequently, research is being carried out to add credentials and identity protection to EAP methods, especially to EAP-TLS. In this latter method, the client certificate is sent in clear text and therefore, an attacker can easily sniff packets conveying the client credentials. To avoid sending identity information in clear text during the TLS session, Hajjeh and Badra (in press) extend TLS with an enhanced, completely backwards compatible mechanism. The client identity protection is provided by symmetrically encrypting the client certificate with a key derived from the TLS master secret,

Hardware Security in WLAN

Many agencies (GAO, 2001) require the use of smart cards to overcome the vulnerabilities of the storage of private and shared keys. In fact, without smart cards, unauthorized access can be easily established to an authorized device (e.g., station) to retrieve confidential and personal data stored on it.

A smart card is a portable and tamper-resistant computer. It provides data security, data integrity, and personal privacy and supports mobility. Furthermore, major application areas including mobile communication use smart card to convey user subscription and identification information as well as to provide user identity and to build computer and network access.

In the 802.1X/EAP context, (Urien & Pujolle, 2005) describes the interface of the EAP protocol in smart cards, which can store multiple identities associated to EAP methods and appropriate credentials. It presents implementations of the EAP-TLS smart cards, which securely stores TLS security parameters, such as client X509 certificate, client private RSA key, and CA public key. For more information regarding the EAP smart card configuration and test steps, please refer to the OpenEAPSmartCard (2006), which is an open Java card platform for authentication in Wi-Fi and WLAN networks.

THE UNIVERSAL ACCESS METHOD

A different approach to authentication and authorization for WLAN is that based on Web-based unlicensed mobile access (UAM), the most prevalent form of access to WLAN. This approach defines a sign-on usage model using the user navigator or Web browser and it is adopted by a number of WLAN hotspots providers. The Web-based UAM approach is very simple. When the user attends to get Internet access through a given hotspot, this latter will redirect the user's browser to a local Web server. After redirection, the user will be invited to be authenticated by entering its credentials (e.g., username, password). These credentials are tunnelled through a secure session, typically established using TLS.

UNLICENSED MOBILE ACCESS

UMA stands for Unlicensed Mobile Access; a technology provides access to GSM and GPRS mobile services over unlicensed spectrum technologies,

including Bluetooth and WLAN. By deploying UMA technology, service providers can enable subscribers to roam and handover between cellular networks and public and private unlicensed wireless networks using dual-mode mobile handsets. With UMA, subscribers receive a consistent user experience for their mobile voice and data services as they transition between networks (UMA, 2005).

The UMA architecture uses the following standard IP-based protocols without any modifications. It uses IP/TCP to provide a tunnel for GSM/GPRS signalling and SMS, IPSec ESP to provide a secure tunnel for user and control plane traffic, IKEv2 (Kaufman, 2005), and EAP-SIM (Haverinen & Salowey, 2006), and EAP-AKA (Arkko & Haverinen, 2006) for authentication and establishing and maintaining a security association between MS and UNC.

EAP-SIM and EAP-AKA introduce the smart card use (e.g., SIM cards). Due to the smart cards advantages cited before, a potential attacker will not be able to access the smart card memory to spoof or retrieve the private and personal data. Moreover, the attacker will not be able to have these data in clear text outside the smart card since UMA is operating over IPSec ESP, which provides a strong authenticated and encrypted session. However, cares must be taken when implementing UMA technology on an open terminal. To have a focus study on the impact of open terminal platforms when UMA technology is implemented with GSM, please refer to Grech and Eronen's (2005) work.

SECURITY PERFORMANCES IN WLAN

Security mechanisms usually involve using of certificates, public-key infrastructures, symmetric encryption/decryption, digest computation, and so forth. Therefore, 802.1X/EAP will add a performance impact, varying upon the deployed security protocol. Several studies have evaluated the security performance of WLAN and the performance impacts of WEP, WPA, EAP-TLS, and other authentication protocols.

Baghaei (2003) provides a study comparison of the following eight security solutions used by 802.11:

1. No security: no security mechanism activated with default configuration.
2. MAC address authentication carried out at the AP.
3. WEP authentication.
4. WEP authentication with 40-bit WEP encryption.
5. WEP authentication with 128-bit WEP encryption.
6. EAP-TLS authentication.
7. EAP-TLS with 40-bit WEP encryption.
8. EAP-TLS with 128-bit WEP encryption.

This study comparison includes an analysis of the effect of different TCP and UDP packet sizes on performance of secure networks. It shows that WEP encryption significantly degrades the

Figure 4. Throughput of TCP, UDP traffic in a congested network

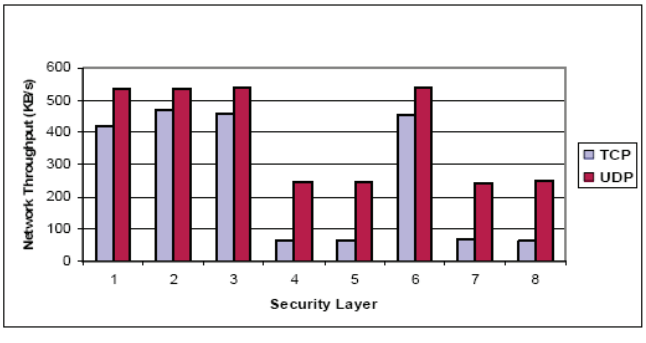
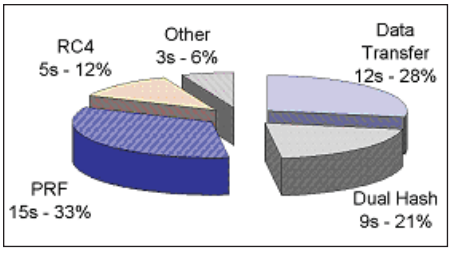


Figure 5. Computing times distribution for a smart card



performance of congested wireless networks. Network performance degradation increased as the number of clients was increased under all security mechanisms.

On the other hand and in order to show the impact of smart cards use within 802.1X/EAP, we implemented EAP-TLS on smart cards, in which performance, benefits, and drawbacks are discussed and analysed by Urien, Badra, and Dandjinou (2004).

Figure 5 shows the repartition of computing times during the authentication phase. The smart card (10 MHz, 8 bits CPU, 2304 bytes RAM bytes, 96 Kbytes 32 Kbytes ROM, 32 Kbytes E2PROM) processes the EAP-TLS protocol in about 5 seconds (Urien & Badra, 2006). Note that benchmarks are performed on a 1 GHz Intel processor PC and only about 50 ms are required to execute an EAP-TLS session. This demonstrates the cost and performance influence of using smart cards, which are required for credentials and private data storing.

CONCLUSION

Wireless technologies have evolved phenomenally over the last few years. Wireless transmission has a big impact on new services and applications because it is the method for data communication for, among others, cellular phones, text pagers, and Wireless LAN 802.11. In this chapter, we focused on WLAN security threats, which extend on several levels, from the identity spoofing to the traffic analysis.

WLAN security risks have increased exponentially as wireless services have become more popular. The risks represent any malicious and undesirable event on the various applications, which possibly suffer from faults facilitating treat concretization. Risks can result in sniffing and hijacking of sensitive and personal data over the link for unprotected Internet access. The consequences are therefore variants (Hurley, 2002). It can eat up bandwidth, but it could pose a darker issue as virus writers can use the access to anonymously send viruses out.

In answer, WLAN defined, among other, the 802.1X standard, providing a framework for authenticating and controlling user traffic to a protected network, as well as dynamically varying and exchanging encryption keys between the wireless entity and the authenticator server. This is done using EAP methods, which are also deployed jointly with the 802.11i and WPA standards. Implementing WLAN technologies in a secure network requires on one hand a combination of these security measures. On the other hand, organizations need to adopt security measures and practices that help bring down their risks to a manageable level. In early 2006, therefore, ISO members voted the IEEE's 802.11i standard for adoption.

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Chapter XLIV
Access Control in Wireless Local Area Networks:
Fast Authentication Schemes

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ABSTRACT

Wireless local area networks (WLAN) are rapidly becoming a core part of network access. Supporting user mobility, more specifically session continuation in changing network access points, is becoming an integral part of wireless network services. This is because of the popularity of emerging real-time streaming applications that can be commonly used when the user is mobile, such as voice-over-IP and Internet radio. However, mobility introduces a new set of problems in wireless environments because of handoffs between network access points (APs). The IEEE 802.11i security standard imposes an authentication delay long enough to hamper real-time applications. This chapter will provide a comprehensive study on fast authentication solutions found in the literature as well as the industry that address this problem. These proposals focus on solving the mentioned problem for intradomain handoff scenarios where the access points belong to the same administrative domain or provider. Interdomain roaming is also becoming common-place for wireless access. We need fast authentication solutions for these environments that are managed by independent administrative authorities. We detail such a solution that explores the use of local trust relationships to foster fast authentication.

INTRODUCTION

Wireless local area networks (WLAN) are rapidly becoming a core part of enterprise network access. The IEEE 802.11 standardization has lead to vendor interoperability and rapidly plummeting prices, making wireless access an economically tantalizing alternative to wired access. Currently, enterprise deployment incorporates support for mobility between access points (AP) as well as security and monitoring solutions. Mobility introduces a new set of problems, not present in a wired infrastructure, due to handoffs between network access points. The implications of frequent handoffs to different APs is that for communication security, the IEEE 802.11 standard requires that the mobile node (MN) has to undergo a full authentication process each time it wants to connect to a new AP. The recent security ratifications from the IEEE task group i (TGi) (IEEE 802.11i, 2004) defined several security remedies for WLANs in the standard IEEE802.11i. According to this standard, the complete (full) authentication process involves the use of 802.1X port-based access control architecture, and provides mechanisms for key management (IEEE 802.1X, 2001). An AAA server such as RADIUS (Rigney, Willats, Rubens, & Simpson, 2000; Rigney, Willats, & Calhoun, 2000) is to be used for authentication and key derivation. Following a successful authentication, the MN and the AP are to undertake a four-way handshake protocol for deriving various encryption keying material. Keying material derived in this way then is used in the encrypted (secure) communication sessions between an AP and the MN. Thus the four-way handshake, which does not involve the AAA server, is a *must* in each secure association of an MN to the AP and cannot be avoided.

However, the authentication process, suggested in the 802.11i ratifications using extensible authentication protocol (EAP) over transport layer security (TLS) can introduce significant handoff delays because it involves the exchange of a round of messages between the MN and the AAA server via the AP. It has been shown that a full EAP-TLS authentication (i.e., the full authentication) can take as long as *1.1* seconds (Mishra, Shin, & Arbaugh, 2004). The delay can only increase when the AAA server is located at the ISP's site, topologically far from the AP site. The longer the delay in handoffs, the longer the outage time experienced by applications. While this kind of delay is acceptable for applications with flexible response time requirements, emerging real-time applications, such as wireless voice-over-IP, have stringent delay requirements (Cisco IP phone). Thus, this kind of network delay and outages are detrimental for real-time applications, especially in frequent handoff scenarios, which hinders the success of wireless local networks to support such popular applications.

The aim of this chapter is, therefore, to provide readers with state-of-the-art knowledge on this significant issue, and solutions as found in the industry and literature. The mentioned issue arises from two directions: (1) intradomain handoffs and (2) interdomain handoffs. Thus solutions are needed for both. While various solutions have been mostly proposed for the first direction, we will show that interdomain, or interprovider handoffs are becoming a common place and need specific solutions that are different from the intradomain solutions because of the involvement of more than one administrative authority in the latter cases.

To reduce the handoff delays due to the exchanges of authentication messages when a MN hands off to a new AP (nAP), there have been several proposals from the industry and the research community. These solutions are targeted for providing fast access when changing APs belong to the same administrative network domain.

However, handoffs within a single domain might not always be the case. There are possible scenarios where different service providers need to collaborate to provide continuous connectivity to roaming users for supporting seamless services. In addition, IEEE 802.11 has lead to price levels suitable for the mass consumer market and small operators. This has caused an explosive trend in the deployment of residential gateways (RG) for home networking and wireless hotspots at city areas by various business owners and hotspot providers.

The capacity offered by these APs and residential gateways (RGs) at various sites may not

be fully utilized since the traffic patterns typically vary considerably over the course of a day. Thus, there will be unutilized capacity that could be offered to active users despite not being their serving provider or AP.

In this model, each WLAN site that is connected to the Internet via an individual RG or AP can be considered as an individual domain as RGs are owned by individual residential consumers and wireless routers (or APs) at hotspots belong to individual providers or businesses. An example of a current operational commercial system building on this principle is the FON (FON Web site) community where individual subscribers share excess capacity with the global FON community and FON itself provides billing support so that used capacity is billed to a user's own account.

If the current deployment trend continues, in dense residential areas it will be common to find a substantially large number of RGs within range. This also provides the opportunity for load-sharing or load-balancing among the RGs by handing off some visiting connections to other RGs within range when the original RG's link utilization or load increases and affects its home traffic. Therefore, we see stationary handoff scenarios emerging in the multiowner RG access network architecture, which can also apply to the commercial city area hotspots. Depending on the load variation, there may be situations when during an active session a visiting mobile node will have to undergo frequent handoffs to many new RGs. The same applies to the city area hotspot architecture.

The previous proposals and implementations mentioned above aim at supporting a single domain where centralized control is an advantage. In the collaborating scenarios between service providers this is not the case since each domain has its own authentication mechanisms that are closed to other parties. In the RG access network or the city area hotspot architecture, such centralized control is not possible since each RG or AP is under its own authority and administration. Hence, a distributed approach is required for multiowner and multiprovider handoff scenarios.

The rest of the chapter is organized as follows. In the next section we provide background information on the port-based authentication-driven access control as suggested in IEEE802.11i, the security ratifications from the IEEE task group *i*. This section equips the reader with the fundamentals of the authentication-based access control process using 802.1X architecture. In the third section we elaborate fundamental proposals found in the literature that provide fast-authentication schemes applicable in the intradomain handoffs. This section also contains a subsection on comparative analysis of the presented proposals. In the fourth section we provide a possible direction that we have proposed for solving the interdomain handoff latency problem because of authentication delays. We sketch some open issues, and finally, we conclude this chapter.

IEEE 802.11I AUTHENTICATION PROCESS

In this section, we provide fundamental information on the authentication-based access control mechanism for IEEE802.11i, the security ratifications from IEEE802.11. IEEE 802.11i includes the use of the architectural framework of IEEE802.1X, the port-based network access control standard for different link layer technologies such as IEEE 802.3, FDDI, IEEE802.11, and so forth. In the standard, there are three entities involved in the authentication process: the supplicant or the user wireless device, the authenticator or the network port (wireless access point), and the authentication server such as the RADIUS server. Figure 1 shows this setup. The 802.1X standard uses *extensible authentication protocol* (Blunk, Vollbrecht, Aboba, Carlson, & Levkowetz, 2003) to support a variety of authentication mechanisms, of which the *transport layer security* (TLS) providing strong encryption and authentication at the transport layer is the most commonly used mechanism (EAP-TLS) (Aboba & Simon, 1999) within 802.11 networks. Next, we look at the functionalities of the entities of the 802.1X framework in light of the 802.11 network setting:

Figure 1. 802.1X setup

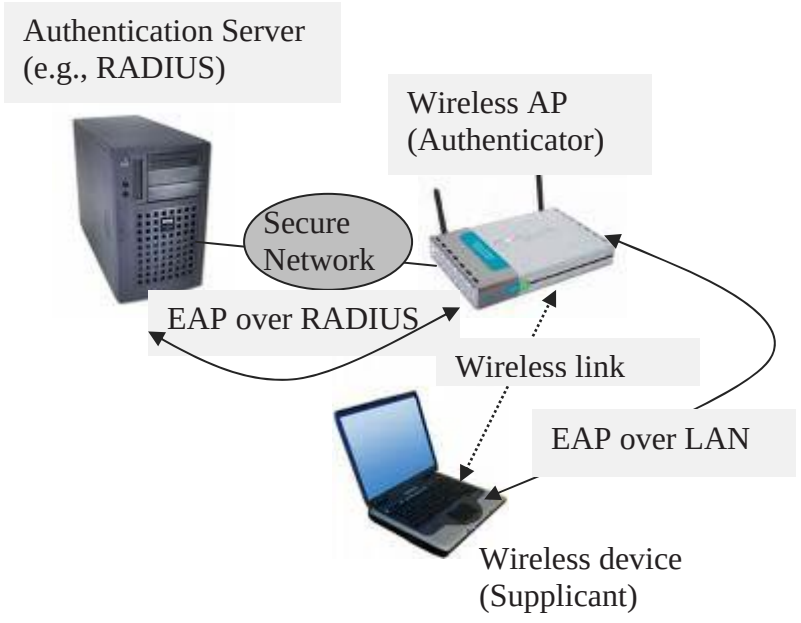
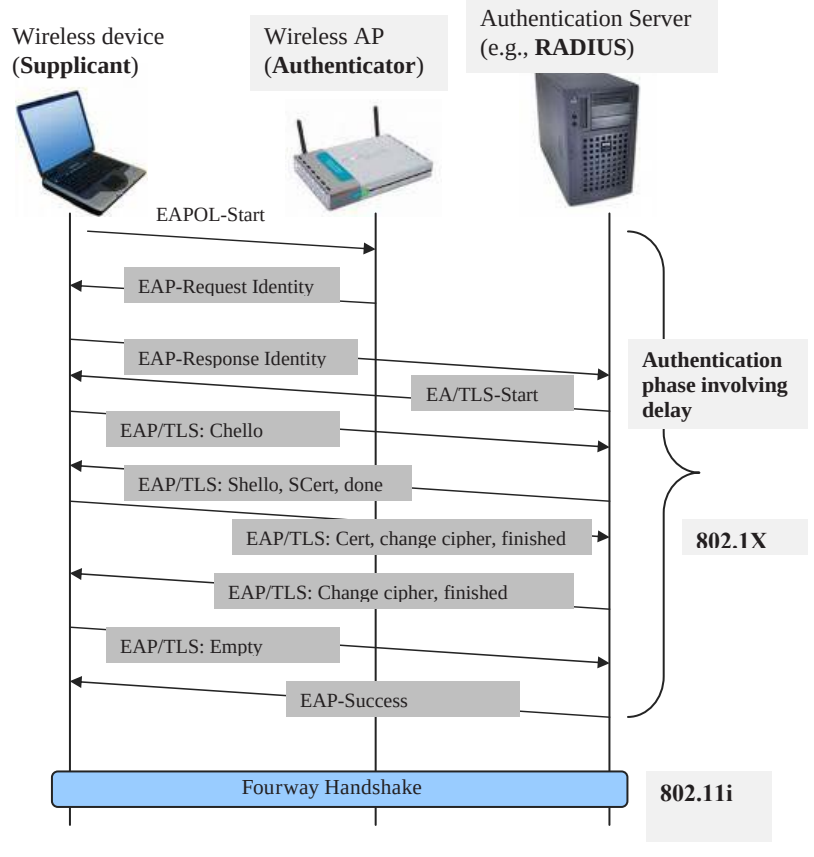


Figure 2. EAP-TLS authentication messages



- **Supplicant:** This is a user device seeking link layer connectivity with a network so that it can use the services offered by the network.
- **Authenticator:** This is the wireless AP providing link layer connections to the user devices. In any network, typically there will be many APs. The authenticator liaises with the authentication server by relaying information to and from the supplicant. When the authenticator receives a success message from the authentication server, it allows the supplicant to establish a link layer connection.
- **Authentication server:** This is a central server which helps the authenticator with the authentication decision based on what it knows about the supplicant and the information supplied by the supplicant.

As EAP, and in particular EAP-TLS, serves as the authentication building block for strong authentication security, we discuss briefly these technologies.

A. EAP: EAP communications are in the form of challenge-response method. EAP uses four basic message types: EAP request, EAP response, EAP success, and EAP failure. After a few rounds of request and response exchange, the supplicant is notified of the outcome using EAP success or EAP failure. Regarding the transport of the authentication protocols used, as EAP does not have any addressing mechanism, EAP messages are encapsulated in EAP over local area network (LAN) (EAPOL) protocol between the supplicant and the authenticator, and as a RADIUS message (EAP over RADIUS) between the authenticator and the authentication server.

B. TLS: Specified in RFC2246, when used in 802.1X, the supplicant and the authentication server will undergo a mutual authentication process. At the root of this process are certificates at both of these entities from a common certificate authority (CA). The results of the mutual authentication using these certificates are a strong secret master key (MK), and an initial set of pseudo-random function which will be used to generate additional keying material. Using this function and the MK, a pair-wise maser key (PMK) is generated. The PMK further produces four pair-wise transient keys (PTKs) when used with particular cipher methods, and are used for origin authenticity and confidentiality of the four-way handshake procedure, as well as for data encryption.

Figure 2 shows the full EAP-TLS authentication steps and messages exchanged. At the end of a successful EAP-TLS authentication (EAP success message), there is a four-way handshake process which ensures that the AP and the MN are active, guarantees the freshness and synchronization of the shared encryption key, as well as binds the PMK to the medium access control (MAC) address of the MN.

INTRADOMAIN FAST AUTHENTICATION SOLUTIONS

One of the most significant features of wireless networks is that it does not restrict users to a fixed connection point (e.g., at a desk) while using the network. As long as the user is within the coverage area of a wireless access point or base station, the network connection keeps alive. The predominant mobility-friendly applications are voice and multimedia that can be supported when the user is continuously mobile. However, primarily due to this kind of mobility, the connections need to be switched from one access point to the next, a process called handoff, when the user crosses the coverage boundary of one AP and moves into the next one. Using 802.11i in wireless LANs, this means that the full EAP-TLS authentication has to be performed each time such handoff occurs. It is well-known that real-time applications, such as wireless voice over IP, have stringent delay requirements and can only tolerate moderate packet loss due to network outage occurring at handoffs. However, it has been reported that a full EAP-TLS authentication process can take as long as 1.1 second (Mishra et al., 2004), a number far too large to support the smooth operation of voice and

multimedia applications in continuous mobility scenarios[1]. This number can only magnify when the RADIUS server is located topologically far from the AP. As the APs in wireless LANs have very small coverage[2], many APs are required to be installed to cover a certain geographical area of a network. Thus, continuous mobility implies that there will be many handoffs during an active real-time application session, even when the user is within the same network (domain). There needs to be mechanisms to cut down the authentication delay of 802.11i for this kind of intradomain handoffs. Below we discuss the IEEE 802.11i proposed solution, and those found in the literature to tackle this issue.

Preauthentication

This is the solution specified within the IEEE802.11i to support fast authentication at handoffs between APs in the same network domain or extended service set (ESS). In this solution, when an MN is connected with an old AP (oAP), it can initiate EAP-TLS authentication with a new AP (nAP) within the same ESS by sending an IEEE 802.X EAPOL-Start message via the oAP to the nAP. The nAP then may initiate the EAP-TLS authentication with the MN. The distributed system of the ESS has to be configured to forward the authentication messages to the oAP for the MN. While still connected with the oAP, preauthentication for the MN is performed by exchanging all the EAP-TLS authentication messages between the MN and the nAP. The process ends when after deriving the new PMK, the nAP sends the first message of the four-way handshake to the MN. The MN and the nAP must cache the new PMK to be used when the MN finally moves to the nAP. Preauthentication can be performed in advance to a group of APs that the MN may select from, for handing off in the future. At time of handoff, there will not be any more EAP-TLS exchanges, and the four-way handshake can be used straight away to resume the connection process.

While the preauthentication mechanism provides a great way to cut down the authentication delay necessary for supporting real-time applications in wireless LANs, in the current form, no mechanism has been used to select the most likely handoff candidate APs. Thus, there will probably be many instances of preauthentications that will not be utilized at all. This is a waste of resources. Also, when there is a large number of candidate APs, this mechanism does not scale and, in addition, puts extra loads on the AAA server. It is to be noted that the scope of the preauthentication is, however, limited to a single network domain or ESS, making it inapplicable in interdomain roaming scenarios.

Proactive Key Distribution

Proactive key distribution has been proposed as a mechanism to provide fast authentication at handoffs within the *same administrative domain*, by *predistributing* the keys to candidate APs in a *neighbor graph* (Mishra et al., 2004). Thus, this scheme avoids the involvement of the AAA or the RADIUS server for distributing the keys to the nAPs *during* handoffs. When the MN will finally move to the nAP, the key will be already there and the local handshake protocol (four-way handshake) can be used to establish the radio link between the MN and the nAP.

The most important concept of this proposal is the use of the neighbor graph. The neighbor graph is the dynamic identification of the mobility topology of the network: a set of APs that the mobile user device potentially could reassociate to. The authors suggest that this set is typically a small subset of all the APs in the wireless network. By selecting the possible candidate APs for handoffs by a particular MN, the cost of proactively distributing the key to these APs are justified and minimized. The scheme utilizes the concept of a reassociation relationship by which the authors mean that two APs have this relationship if it is physically possible for a given MN to handoff from one to the next. Thus, this relationship depends on factors such as physical distance between two APs and placement of the APs. The authors suggest that the neighbor graphs can be autonomously learned and maintained by the wireless network, and can be maintained either in a centralized or distributed

manner. In their implementation, the authors have stored this information in the centralized manner, in the RADIUS server.

The authors propose that instead of distributing the original PMK to all the neighbor graph APs, the PMK is used to derive PMKs depending on the instance of reassociation (e.g., n^{th} reassociation) using a proposed equation. Special RADIUS messages have been also introduced to aid the key distribution process: NOTIFY-REQUEST, NOTIFY-ACCEPT, and ACCESS-ACCEPT. Once the MN completes a full EAP-TLS authentication, the AAA server sends a NOTIFY-REQUEST message to all the APs in the neighbor graph. This message informs the APs that a given MN may roam to their coverage. It is up to the APs to decide whether they want the security information (the PMK) for the MN. If the AP decides to get the security information at this stage, it sends a NOTIFY-ACCEPT message to the AAA server, and the AAA server sends an ACCESS-ACCEPT message in return to the AP containing the appropriate PMK and an authorization for the MN to remain connected to the network. From the experimental results, it has been shown that the average latency of the full authentication reduces to around 50ms from that of 1.1 second.

The scheme provides a practical and feasible way for maintaining the quality of real-time applications while the MN moves about in the same network. However, this imposes extra functionality and loads on the AAA server, because it has to send requests to candidate APs asking if they want the security key for the MN before it hands off to the APs. This centralized approach where a single AAA server controls and manages the key distribution will suit well the scenarios where the WLAN sites are all under the tight control of one central AAA server such that the server can derive and decide on the candidate APs for the MN's next move. This proposal will not be directly applicable to interdomain roaming scenarios.

The proposal from Mishra et al. (2004) has similarity with preauthentication proposal from IEEE 802.11i in the sense that (some) steps of the authentication process is initiated even before the MN moves to the nAP, that is, the proactive nature of the schemes. The two proposals differ in the sense that in preauthentication, it is up to the MN to choose (using no particular guideline) APs in the network to complete authentication before it performs the next handoff, but in the case of proactive key distribution scheme, *only* the APs the neighbor graph can get the PMK (some APs in the neighbor graph may decide not to ask for the key at this stage). Also, the predistribution of the PMK scheme does not involve the MN in the process of distributing the PMKs to the neighbor graph APs, whereas the preauthentication scheme involves the MN to complete the preauthentication process with the nAPs.

Proactive Key Caching

An industry solution, namely proactive key caching (PKC), is an extension of Airespace Inc.'s[3] wireless enterprise platform, developed along with Funk Software[4] and Atheros Communications (Atheros Communications). In PKC, the MN can use the same master key to roam across an *Airespace network*, visiting one AP to the next. This eliminates the need for RADIUS authentication at each handoff; only the four-way handshake will be required. Airespace has a centralized policy engine for creating and maintaining security parameters across the *entire enterprise*. The use of the central policy engine in the network also leads this solution to be centralized and suitable only for a single administrative domain.

Predictive Authentication

This proposal from Pack and Choi (2002) is a predictive-authentication scheme based on the selection of a frequent handoff region (FHR) which works in a centralized manner. The main idea is to formulate a FHR consisting of a number of APs in a public access LAN by using a FHR selection algorithm, and taking into account the user mobility and traffic pattern. The FHR APs are the ones that the MN is likely to associate with in the near future. The MN is preauthenticated to all the APs within the FHR so that when the MN handoffs from one AP to the next within that FHR,

there is no time wasted in communicating with the RADIUS server.

The authors use the notion of movement ratio between APs which determines the handoff probability of a particular AP in the network. The movement ratio is affected by the user mobility and AP location. Movement ratio between APs can be measured by using an event logging system which logs the handoff information including login time and handoff times to different APs. Using a given equation and the log information, the handoff ratio is then calculated. To determine the FHR APs, the users' service level is considered as well. If the user can tolerate service disruptions during handoffs, less APs can be included in the FHR, and vice versa. Obviously, if there are more APs in the FHR, there will be more resources used for preauthenticating to them than if there were less APs in the FHR. Thus this differentiation based on service level serves an important purpose.

The key distribution in IEEE 802.1X has been modified to suit this scheme. Although the MN sends an authentication request to the AAA server via its current AP, the server sends the authentication response message (EAP success message) to APs in the FHR. The FHR APs keep the authentication information for the MN in soft state for a certain period, let us call it preauthentication validity period. If the MN does not handoff within that period, the information is no longer useful and the MN will then have to perform a full authentication if it handoffs after that period to that AP. If the MN moves to an AP in the FHR within the preauthentication validity period, the reassociation with the new AP is fast as it only uses the exchange of a couple of messages locally between the AP and the MN.

This scheme has much similarity with the preauthentication scheme, with the difference being that the predictive authentication proactively authenticates to a *group of APs* that the MN is more likely to handoff to, rather than just any new or next *APs* in the network selected by the MN. Predictive authentication is also a centralized solution in that the MN does not have to decide which AP(s) to preauthenticate to; the network (the AAA server) takes charge of that decision.

INTERDOMAIN FAST AUTHENTICATION

Up until now, we have discussed proposals that are designed for reducing the authentication delay of the radio link layer establishment when a mobile device moves from one AP to the next within the same network administrative domain. While these are the most common handoffs, roaming such as in wireless hotspot areas served by multiple providers is becoming more common these days, especially in the CBD areas of big cities. For example, the CBD areas may be covered by small business owners such as Starbucks, big providers such as T-mobile, and nonprofit providers such as the city council. The wireless networks (hotspots) from these entities belong to different administrative domains. Consider the following scenario. There is an overlap between a public network in a coffee shop and a council-operated open wireless mesh network. The council is providing a free service to the public and the coffee shop provides access to paying customers. Despite the business model, for the success of these networks, they must consider supporting real-time session continuation, thus we would need solutions to make the authentication speedy in these multidomain handoff scenarios. Other network setups that would require this kind of solutions can be residential neighborhood wireless networks, also known as community wireless networks as mentioned in the introduction section, where the neighbors want to share their broadband capacity over the wireless access networks they have at their individual premises. Such sharing has been envisioned by various researchers (e.g., Landfeldt, 2006; Thompson, 2006; Raniwala, 2005).

The solutions discussed so far cannot be directly applied to the interdomain handoff scenarios. The main reason is the tight administrative control that the individual domains operate in. The previous solutions also use central decision engines or centralized servers for key distribution, and so forth. Individual domains have their own mechanisms to manage handoffs, and would rather keep it to themselves. One network does not necessarily trust the other when it comes to access control. To ad-

Table 1. A comparison of the fast authentication schemes

Scheme Name	Initiated by	# of nAPs considered	nAP involvement	Applicability
Preauthentication	MN	Variable, selected by the MN	Decided by the MN	Intradomain handoffs
Proactive Key distribution	RADIUS server	A subset of APs in the network; determined by the neighbor graph	Decided by the nAP concerned	Intradomain handoffs
Predictive Authentication	RADIUS server	A subset of APs in the network; determined by the FHR	Decided by the RADIUS server	Intradomain handoffs
Proactive Key Caching	Centralized policy engine	All APs in the network	Centralized policy engine	Intradomain handoffs

dress this gap, we have proposed a "trust-cloud" key sharing model (Hassan & Landfeldt, 2006).

Trust-Cloud Key Sharing

According to our interdomain fast-authentication scheme based on a concept of "trust clouds," a trust cloud is formed among neighboring access points based on a relationship among the owners of the access points. The scheme enables fast and simple authentication for mobile devices that move between access points belonging to different administrative domains such as different ISPs. Used together with an appropriate routing scheme, the scheme enables continuous service of delay sensitive flows even while roaming between different access providers. We define the following terms:

Trust Link: A trust link defines the trust relationship between any two given RG[5]. RG_i and RG_j have a trust relationship between them if they agree to take part in key sharing for visiting mobile nodes between them.

Trust Cloud: A trust cloud is a collection of trust links for a given RG. Every RG has a different trust cloud. One RG can appear in many trust clouds, depending on its relationship with other RGs.

The model is a security key-sharing scheme which works on the basis of AP-to-AP (or RG-to-RG, network-to-network/hotspot-to-hotspot) trust. Unlike the implicit trust among the APs within a single administrative domain or an ESS, this trust is not implicit and is a translation from the trust among the AP-owners through a relationship with a third party such as an ISP or indeed through personal relationships if the community does not operate with a subscription-based model. For example, in community networks, the network operation is dictated by personal preferences, thus even if two AP-owners (or WLAN owners) share the same ISP, there is no guarantee that they would trust each other. This is the difference from neighborhood networks with federated networks such as FON.

In our model, the serving AP[6] of a visiting mobile node (VN) will share the key of the MN that is currently attached with it, within its trust cloud. So, depending on the number of APs in the serving AP's trust cloud, some of the APs in the hotspot area will have the key of the VN ready to be utilized for fast authentication when the VN hands off to one of these APs, and that AP will share the key further among its trust cloud APs. In our model of interdomain access points, provider-provider (or AP-AP, or RG-RG) trust is not necessarily transitive: if RG X trusts RG Y and RG Y trusts RG Z, it does not necessarily mean that RG X trusts RG Z. Moreover, as this trust may have to do with personal preferences, it is not necessary to be symmetric: RG X trusts RG Y does not necessarily mean that RG Y trusts RG X. Initially, we have simulated symmetry in the trust relationships between a given RG pair, and also that trust is not transitive as it depends on the relationship or understanding between any given pair of RG (or RG-owners). This means that if RG X trusts RG Y, RG Y also trusts RG X. However, we have also simulated with the symmetry being relaxed thus two RGs may have uni- or bi-directional trust relations, thus we deviate from a nondirected trust graph to a directed one. By using the concept

of trust clouds in the area, we will see pockets of fast authentication enabled coverage area, and *not* an entire coverage area of federated fast authentication areas. Therefore, we would still require strong authentication mechanism provided by the EAP-TLS in this setup as not all the handoffs will be able to utilize fast authentication.

The fast-authentication for interdomain sites is achieved through cooperation among the trust cloud members. The approach is distributed without a central authentication server being involved in distributing the security master key to the access points belonging to the trust cloud. We have proposed two algorithms for mobile visiting nodes to select RGs to perform authentication at handoffs: trust-aware and trust-unaware. In the trust-aware handoff algorithm, the MN needing to handoff to a new RG actively seeks to handoff to an RG that is trusted by its prior-move RG, thus it has to keep track of which RGs are trusted by its prior-move RG. In the trust-unaware handoff though, the MN just seeks to handoff to a suitable RG (e.g., an RG that has low load and can accept more connections) but does not care about the fast authentication possibility as the RG it hands off to may or may not be trusted by its prior-move RG.

Performance Evaluation

We have carried out simulation-based performance evaluation. The scenarios we model are a VN trying to complete a series of communication sessions by utilizing the unused capacity of nearby RGs within its wireless communication range (RG hotspot). There are a total of N RGs in the hotspot area. The VN can sense the current load of each RG from their beacons, and can only associate with an RG that is lightly loaded. An RG is modeled as a two-state Markov chain where the states of an RG alternate between heavily loaded and lightly loaded. The time spent in each state is exponentially distributed with means (L) selected to obtain a given fraction of time an RG spends in the heavily loaded state7.

If an RG switches its state from lightly loaded to heavily-loaded while a VN session is in progress through that RG, the VN session will have to handoff to another lightly-loaded RG using one of the two trust cloud handoff algorithms, or the trustless one described in the previous section. If no lightly loaded RGs are available, the session is prematurely terminated.

The activity of the VN is modeled using the well known on-off process. When the VN completes a session, or a session is prematurely terminated, the VN enters a silence mode before initiating another session. The session and silence mode durations are exponentially distributed. Mean session duration is denoted by *S*. Once the VN enters the silence mode, its security association with a given RG becomes invalid (an inactivity timer is implemented within each RG, upon expiration of which the security associations of the VN become invalid). Consequently, the VN must go through the full security association process (full authentication involving the AAA server) at the start of each *new* session, even if it continues with the current RG.

The primary performance variable that we measure is the number of times a full authentication is needed for a session on average, since the goal is to reduce this variable. This number is basically one (for the initial association) plus the number of handoffs that require full authentication.

Figures 3 and 4 are two representative graphs from our simulation studies. First of all, we see that our trust-based handoff schemes, be it aware or unaware, achieves much lower per session full authentication than the usual no-trust or trustless

Figure 3. Full authentication vs. mean session time (S)

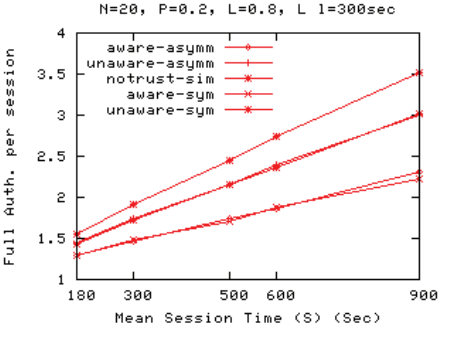
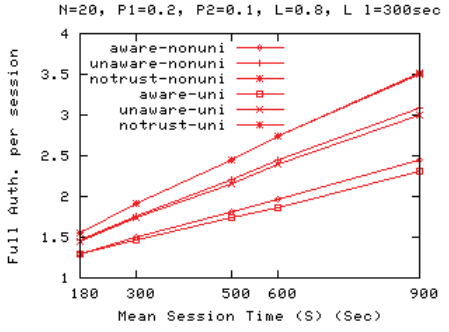


Figure 4. Full authentication vs. mean session time (S): Trust symmetry relaxed



cases. Further more, Figure 3 shows a comparison of symmetric and symmetry-relaxed trust relations in a hotspot area covered by 20 RGs where links may or may not be symmetric. In this simulation, we have used the same trust probability value (P) of 0.2 for both symmetric and asymmetric scenarios (uniform trust probability). As this value is the same for all these cases, we see no difference in the performance. The impact of asymmetric trust relations comes in play when we consider different probability values in deciding trust links in the forward and backward directions for a given pair of RGs (nonuniform). The results then deviate from the case of symmetric trust model. We can observe this in Figure 4 where we have selected two different trust probabilities for the forward direction (P1=0.2) and the backward direction (P2=0.1). In this figure, as the two trust probability values are very close to each other, although we see a difference between the asymmetric uniform and nonuniform cases, the differences are not large. We further simulated an asymmetric nonuniform trust model which we found achieved much lower full authentication per session. In the uniform cases, we used P = 0.2, while in the nonuniform cases, we used P1=0.2 and P2=0.8. Thus we see that the handoffs benefit from the nonuniform asymmetric trust model as the probability values are different and the trust clouds improve because of the higher probability value P2.

Open Issues

The trust-cloud model provides a conceptual way forward in solving the interdomain lengthy authentication issues. However, to make this concept a reality, much more work is required. For example, work is needed to solve issues and answer questions such as what governs trust between providers or APs when we are talking about fast connection administering from neighboring providers or APs, how to formulate the trust groups automatically and in a scalable manner, what is the feasibility of implementation of such solutions, and so on. We are currently focusing on these.

CONCLUSION

Current access control mechanisms in the standard for IEEE802.11 wireless local area networks cannot support continuity of real-time streaming applications in mobile environments where the session has to handoff from one AP to the next. Handoffs involve delay in a few steps, one being the authentication process. In this chapter, we have provided a comprehensive guide on leading proposals for reducing the authentication delay. We have covered both inter and intradomain fast-authentication solutions. Fast-authentication solutions are an integral part of making the AP-switching fast enough to support delay-constrained popular applications.

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KEY TERMS

FHR: A group of wireless access points in a public access LAN to whom the predictive authentication will be performed (Pack, 2002). FHR is selected by using a FHR selection algorithm, and taking into account the user mobility and traffic pattern.

Handoffs: Changing network link-layer connection from one network access point or network port to another one.

IEEE 802.11: Also known as Wi-Fi, this is a set of standards for WLANs from the IEEE 802 working group 11.

IEEE802.11i: An amendment to standard 802.11 to specify security mechanisms for Wi-Fi networks.

Neighbor Graph: A collection of APs that the mobile device is likely to handoff to in its next moves (Mishra, 2004).

Network Access Control: Used for security purposes. Network access control determines who (or which device) to give access to the network.

Trust Cloud: A trust cloud is a collection of trust links for a given access point or residential gateway (RG) (Hassan, 2006).

Trust Link: A trust link defines the trust relationship between any two given RG (Hassan, 2006).

Wireless Networks: Networks (of computers) that allow network nodes (e.g., user devices) to connect to the network infrastructure without any wire, typically using short range radio.

WLANs: Wireless local area networks. Local area networks that allow every computer to use a wireless LAN card with which it can communicate with other systems.

ENDNOTES

1 Typically, the overall latency of handoffs should not exceed 50ms.

2 For IEEE 802.11b, the coverage range is no more than 100-200 feet, as compared to the cellular coverage area in cities which is around 2640 feet, and more in the rural areas.

3 Airespace later was acquired by Cisco Systems (Cisco Systems Web site)

4 Funk Software has now been acquired by Juniper Networks (Juniper Networks)

5 In this section, RG, AP and wireless routers can be treated equally to mean wireless AP-type devices not belonging in the same domain, but to different domains.

6 In the interdomain handoff model, especially the trust-cloud model, the APs (or residential gateways-RGs, in the case of community networks) belong to different owners, and domains. APs and RGs are also used interchangeably here.

7 $L = \frac{L_h}{L_h + L_l}$, where L_h and L_l are the mean values for the sojourn times in the heavily and lightly loaded states, respectively.

Chapter XLV
Security and Privacy in RFID Based Wireless Networks

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ABSTRACT

Mass deployment of radio-frequency identification (RFID) technology is now becoming feasible for a wide variety of applications ranging from medical to supply chain and retail environments. Its main draw-back until recently was high production costs, which are now becoming lower and acceptable. But due to inherent constraints of RFID technology (in terms of limited power and computational resources) these devices are the subject of intensive research on how to support and improve increasing demands for security and privacy. This chapter therefore focuses on security and privacy issues by giving a general overview of the field, the principles, the current state of the art, and future trends. An improvement in the field of security and privacy solutions for this kind of wireless communications is described as well.

INTRODUCTION

Radio-frequency identification (RFID) has its roots in WWII when it was used for the first time to distinguish British from German aircrafts. An aircraft was challenged to communicate a certain piece of information and on this basis a decision was made on whether to attack it or not.

This principle is the core of contemporary RFID technology, although, of course, the implementation technology is significantly different. It is now based on low-cost integrated circuits (ICs) called *tags*. Due to the ability to currently store up to two kilobytes of data on these tags, they constitute a very attractive technology in many areas. These include manufacturing, supply chain management, inventory management, healthcare applications, air-transportation, and so forth. All items (in containers) can be scanned together, while each item can be uniquely identified and traced. These properties give RFID technology significant advantages over existing bar-code systems that currently serve for low level, operational acquisition of data in the above mentioned business environments.

These appealing properties also have drawbacks, many of them in the area of security and privacy. But as RFID is already finding its place in contemporary information systems (ISs), these issues need to be addressed seriously, which is the goal of this chapter. In the second section, the background of RFID technology is given. In the third section, threats are described and countermeasures are given. In the fourth section anticipated future trends are discussed. There is a conclusion in the fifth section, while the chapter ends with references and key definitions.

BACKGROUND OVERVIEW

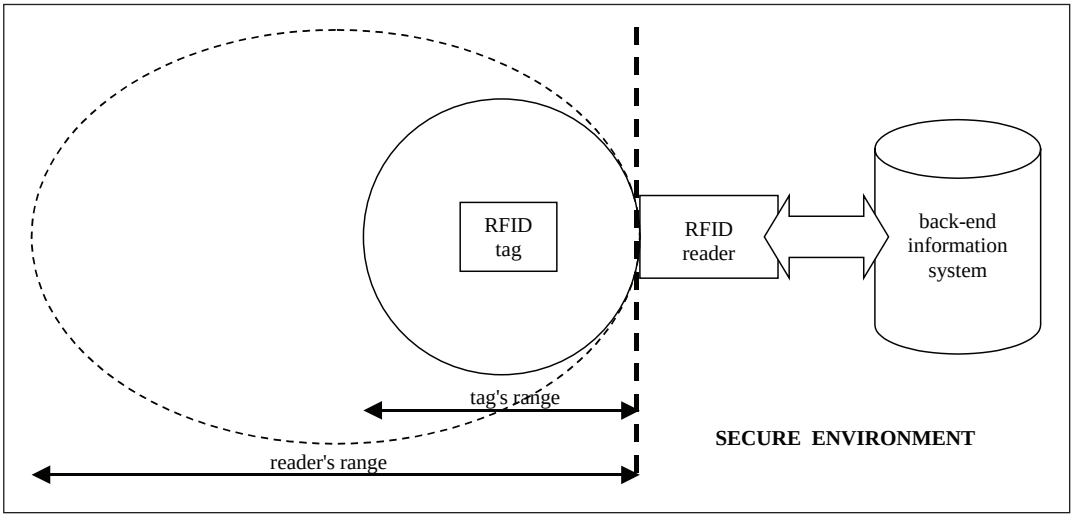
Some definitions have to be given first. One basic definition in the area of computer (communications) security states that security means minimization of vulnerabilities of assets and resources (ISO, 1989). *Wireless security* thus means minimization of vulnerabilities of assets and resources when communicating information in electro-magnetic media through a free-space environment. Finally, *RFID technology* will be defined as wireless identification technology which operates on radio frequencies and deploys low-cost ICs.

A model of RFID environment is described in Figure 1. It consists of *tags* (also called responders) and *readers* (also called transceivers). This is the front-end of RFID applications, which have their back-end in database management systems, where they are integrated with the rest of the IS (see Figure 1). It is generally assumed that RFID security and privacy is concerned with the front-end part (the left-hand side of the dashed vertical line in Figure 1). This is actually the part that is covered by the reader's signal; the tag's signal usually falls within its range.

Tags consist of a microchip and an antenna, both encapsulated in polymer material. The microchip has encoded data, called *identification* (ID), which typically include the manufacturer, brand, model, and serial number. Communication takes place on radio-frequencies, for example, from 125 kHz to 134 kHz for security cards and from 800 MHz to 900 MHz for retail applications (Roussos, 2006). However, increasing the frequency means increased accumulation of signal in bodies containing large quantities of water or in metal.

Communication is achieved by electromagnetic coupling between readers and tags. A reader transmits a signal, which induces a voltage in the tag's antenna. This coupling provides sufficient power

Figure 1. A model of the RFID security and privacy environment



for a tag to respond (after performing some calculations if required). If a tag is powered through this coupling, it is called a *passive tag.* However, if a tag has some source of energy, for example, a battery, it is called an *active tag.* Each type has certain advantages and disadvantages. Passive tags are cheap, but remain active until being explicitly destroyed. They have a low operating perimeter (typically 3 meters) with a relatively high error rate. In contrast, active tags have a greater operating perimeter (up to a few hundred meters), lower error rate, and cease functioning when the source of power is exhausted. However, they are significantly more expensive. Both kinds of tags can be read only, write once-read many, or rewritable.

The main barrier to mass-deployment of RFID tags is their price. A wish-price is limited by five cents, but depending on quantities and using current technologies, many application niches can already be covered. The total cost consists mainly of cost of an antenna, which can be from €/US$ 0.01 to €/US$ 0.02, cost of silicon, and IC production; silicon typically costs €/US$ 0.04/mm^2 (Weis, 2003), while IC production depends on the number of logical gates, that is, technology. But roughly, the cost ranges from €/US$ 0.025/mm^2 with 1500 gates/mm^2 to €/US$ 0.08/mm^2 with 60.000 gates (Weis, 2003).

A typical communication channel with a passive RFID is asymmetric. This means that forward communication, that is, communication from a reader to a tag, has one order of magnitude larger in range than backward communication, that is, from the tag to the reader. In the former case this is typically up to 100 meters, while in the latter case this is typically up to 3 meters. The reason, of course, is the power consumption constraint, which means that practical applications are limited to a range of up to 3 meters.

Thus, the cost factor dictates that a typical RFID, or a reference RFID implementation, is currently expected to have the following characteristics. It is passively powered and has 96 bits of read-only memory. These standardized bits serve to carry the *tag's identity*, which is unique for each tag (these IDs are stored in silicon by an imprinting process). A chip operates at 20,000 clock cycles, providing 200 read operations per second. An algorithm to respond to read primitives from a reader may be probabilistic (e.g., Aloha (Prasad & Rugierre, 2003) or deterministic (e.g., a binary walking tree) (Juels, Rivest, & Szydlo, 2003). With such algorithms, a single tag can be identified and isolated. The related process is called *singulation*. Finally, the number of available gates that can be devoted to security operations is in the range of 400 to 4,000.

The above estimates are based on figures from Weis (2003) by applying Moore' s law, which states that for the same price the available processing power doubles every year and a half. It is therefore clear that processing resources to support security in RFID environments are very limited and lightweight cryptographic solutions thus provide an answer to this problem.

Moore's law also implies that there is always a point where "ordinary" cryptographic algorithms become feasible for computationally weak devices. An example of a thick RFID implementation, which is based on AES to provide authentication, can be found in the work of Feldhofer, Dominikus, and Wolkerstorfer (2004). Despite this, a permanent need exists for lightweight cryptographic protocols and also algorithms. One main reason is the gap between ordinary devices where space and power consumption are not a serious concern (e.g., tag readers, desktop systems), and weak devices with limited space and power consumption (e.g., RFID tags, smart-cards). This gap means that increased processing power affects both kinds of devices equally; in the case of a cryptographic algorithm, the key-length of this algorithm is extended.

As a consequence, weak devices are again less protected because they cannot deploy such intensive computations with enlarged keys. Further, if the above use of a cryptographic algorithm can be seen as a kind of variable cost (the longer the key, the higher the processing overhead), cryptographic protocols can be seen as a fixed cost. Note that cryptographic protocols are ordinary communication protocols that deploy cryptographic algorithms, and cryptographic protocols are often referred to as *security services*, while cryptography algorithms are referred to as *security mechanisms*. Both kinds of costs contribute to the total processing power

requirements, and have to be kept low while at the same time enabling a comparable level of security to weak devices. This leads to a whole new research area (Juels, 2004).

RFID Threats and Countermeasures

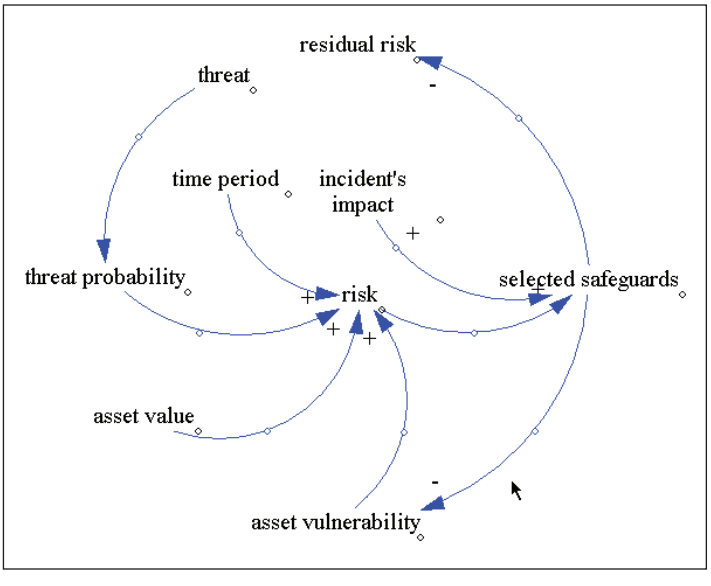
The very basic threat to each and every tag is that it remains active when it is no longer supposed to be active. To counter this problem, RFID logic may implement *kill operation*, which means that upon receipt of a certain communication primitive, the tag becomes permanently inoperative by, for example, blowing a fuse in its circuitry. A more bullet-proof solution is exposure of RFID to microwave radiation that melts its metalized layer.

Risk management drives each and every provision of security and privacy in ISs. A typical process is depicted in Figure 2. It starts with the identification of assets A ($A = \{a_1, a_2, \ldots, a_n\}$) and threats T ($T = \{t_1, t_2, \ldots, t_m\}$) to those assets. For each asset and threat, that is, Cartesian product $A \times T = \{(a_1, t_1), (a_1, t_2), \ldots, (a_n, t_m)\}$, related vulnerabilities are identified together with the likelihood of a threat to get into interaction with the asset during a certain period of time. On this basis, the estimated damage $D(a_i, t_j)$ caused by interaction between asset a_i and threat t_j during this period is calculated. The result presents the upper bound for investment in safeguards. A certain degree of risk, called residual risk, is usually accepted and taken into account. This often makes sense economically. But in the majority of cases, a threat cannot be completely neutralized (Trček, 2006).

The challenging parts of this process are identification of threats and their probability. For identification of threats in RFID environments a comprehensive taxonomy from Garfinkel, Juels, and Pappu (2005) can be used. The first four threats are related to corporate security, and the rest to personal privacy:

- **Corporate espionage threat:** Tagged products may enable remote acquisition of supply chain details like logistics details, volumes, and so forth.
- **Competitive marketing threat:** Tags may enable access to customers' preferences and use the data gathered for competition.
- **Infrastructure attacks threat:** Where RFID is central to a competitor's advantage; disruption of RFID operations becomes an important point for attack.

Figure 2. Risk management process



- **Trust perimeter threat:** Gathering additional volumes of data through RFID introduces new challenges related to sharing information in a trustworthy way.
- **Action threat:** Individuals actions may be monitored.
- **Association threat:** When tagged products are associated with an individual's ID (e.g., loyalty programs), these persons can be associated not only with the type of product, but with the exact product, due to its unique ID.
- **Location threat:** Tags can be triggered by covert readers at various locations to reveal a person's location.
- **Preference threat:** Tags disclose preferences of customers and help to identify, for example, more wealthy ones.
- **Constellation and transaction threats:** Constellation threat is similar to location threat, but in this case the identity of a customer is not known. Despite this, a particular person can be spotted and traced. Further, chaining one constellation threat with another, a whole chain of actions, or transactions, becomes traceable.
- **Breadcrumb threat:** When products are disposed with their original tags, an attacker may use them and is tracked with falsified identity. This is actually just another kind of identity theft.

On top of all this, a fundamental threat exists, called tag cloning, and such cloning has been successfully demonstrated (Bono, Green, Stubblefield, Juels, Rubin, & Szydlo, 2005). What countermeasures are at our disposal?

The basic option was mentioned at the beginning with the physical destruction of a tag (e.g., by exposure to microwaves or implementation of a logical kill command that makes chip inoperable). But the fact is that the latter approach often has flaws in implementations: logically killed tags may remain active or be reactivated (Roussos, 2006). In many situations, it might be even beneficial to keep these tags active; for example, tagged items may be used for smart-home applications or to help disabled people.

The most common approach to security and privacy is by deploying cryptography. Using cryptographic mechanisms (e.g., symmetric and asymmetric cryptographic algorithms, strong one way hash functions), the following cryptographic services can be implemented (ISO, 1995):

- **Authentication:** This ensures that the peer communicating entity is the one claimed.
- **Confidentiality:** This prevents unauthorized disclosure of data.
- **Integrity:** This ensures that any modification, insertion, or deletion of data is detected.
- **Access control:** This enables authorized use of resources.
- **Nonrepudiation:** This provides proof of origin and proof of delivery, such that false denying of the message content is prevented.
- **Auditing:** This enables detection of suspicious activities and analysis of successful breaches. It provides evidence when resolving legal disputes.

In case of RFID tags, authentication, confidentiality, and access control can be applied to counter threats described at the beginning of this section. But to make these security services operational, key management (i.e., handling of cryptographic algorithms' keys) has to be resolved (Trček, 2005). This is a complex issue in open environments and has been known as such for almost two decades. Suffice it to say that only very simple key management schemes are acceptable for RFID environments.

With regard to security and privacy, it is required that authentication, and consequently access control, is provided only to legitimate readers. Further, rogue readers should not be disclosed a tag's ID, but should also be prevented from tracing a tag, regardless of the inaccessibility of its ID. Put another way, when rogue readers interact with a tag, it should be practically impossible (i.e., computationally difficult) to link the multiple manifestations of a tag to this very tag.

An example of recent solutions that meet these requirements is the YA-TRAP protocol (Tsudik, 2006). However, to demonstrate a typical simple authentication RFID protocol, an example by Weis (2003) is given. In this case, RFID contains a derivative of some key, from which it is computationally hard to obtain the real key. This derivative, called metaID, can be a cryptographically strong hash of the key. The tag authenticates the reader as follows:

1. The reader queries a tag to send its metaID.
2. After obtaining metaID, the reader looks up the internal table to find the corresponding key, which is unique for each tag. It sends this key to the tag.
3. After obtaining the key, the tag hashes this key and compares it with its metaID. If values match, the tag provides its full functionality.

It can readily be observed that confidentiality is not used in the above scenario. This means that the communicated data are exchanged in plain and can be read by an adversary. In the above scenario, it suffices to intercept the key, and afterwards to falsely authenticate to tag.

This is not the only threat to confidentiality. Confidential data are stored on RFID, the most sensitive piece being its ID. Due to processing requirements and key-management problems, the tendency is to store data in plain. In this case, many other kinds of attacks can be applied that exploit a tag's tamper resistance, and may consequently lead to the tag's cloning (Anderson & Kuhn, 1996). Such attacks can be prevented by careful circuitry design principles that are common in smart-card design (e.g., scrambling of memory addresses, proper positioning of the memory layer within the integrated circuit, and inclusion of dummy components).

But, as is always the case with security and privacy in ISs, one should not rely solely on cryptography. One alternative architectural approach is the use of tag pseudonyms (Garfinkel et al., 2005). In this approach, each tag is given a cycling sequence of pseudonyms that are chosen to reply to reader requests. But by repeatedly scanning the same tag the whole cycling sequence would be discovered. A solution is to throttle the queries, that is, to use each pseudonym for some extended period of time.

Another option is blocker tags that are based on the already mentioned tree-walking algorithm. The singulation process deploying this algorithm uses a k-bit identifier represented as a binary tree. Each leaf in this tree is the tag's ID. The algorithm goes as follows:

1. The reader starts at the root (depth d=0). To decide whether to proceed along the subtree with 0 or the subtree with zero, it first emits 0.
2. If all tags broadcast 0, the reader proceeds by stepping one level down to the subtree beginning with 0 (depth d=1). If all tags broadcast 1, it steps one level down to the subtree beginning with 1 (depth d=1). If the reader receives both zeros and ones, it proceeds down both trees.
3. The procedure is repeated at each level (the total depth d of the tree equals the number of bits that are used for identifiers, that is, d=k), until only one singular tag is responding.

To spoof the reader, a blocker tag simply emits both bits 0 and 1, which means traversing the complete tree. This reply actually forces the reader to do an exhaustive search on the whole set of 2^{96} combinations, which is impossible. Such a tag would, of course, disrupt all operations. Thus only a subtree of the whole ID space can be allocated to privacy protecting bits (e.g., only that subtree that starts with bit 1). When a reader would enter such a subtree, it would cease the process of further singulation.

Another option is to regulate the range of emitted signal from a tag (Fishkin & Roy, 2003). Based on the strength of a signal, a tag can calculate an estimated distance to the reader and adapt its emitting power to the level, at which signal-to-noise ratio is

such that a reader is able to read the reply. Other devices that are out of this range are automatically disabled from tracing the response.

Finally, we propose a new hybrid technique called one-time pseudonyms. This technique deploys the idea of tag pseudonyms and one-time password principle, which was proposed for the first time by L. Lamport (1981). The principle goes as follows. Take a seed value S_0 and apply a strong one-way hash function to obtain the value S_1 = hash(S_0). Next, calculate S_2 = hash(S_1), S_3 = hash(S_2), and so on. Now, when a tag is to be identified by a reader, the reader sends an integer that denotes the index of the iteration to be done on the seed. Of course, in the case of RFIDs, the unique ID is assumed to be used as a seed.

From the point of background (secure environment) operations, these one-time pseudonyms introduce a workload comparable to that for ordinary pseudonyms. The advantage is that there is no need for a logic circuit to throttle the queries (i.e., to change pseudonyms only every few minutes). Further, the cycle of one-time pseudonyms is not deterministic. Thus it is much harder for an attacker to follow the tag to collect the complete sequence, which is the case with the basic tags pseudonyms technique. There is a slight drawback with this technique if a large number of iterations are required. A straightforward possibility would be to limit the highest index (number of iterations), while another approach would be to store in an RFID, for example, each 20th iteration of its hashed ID. This would also significantly expand the range of applicable iterations, because the upper limit for this technique presents a computation load that is related to the response of a tag and to power consumption.

FUTURE TRENDS

With regard to cryptography, it is anticipated that encryption of RFIDs content will become the norm in providing confidentiality. Basically, in many scenarios it is not necessary that a tag be capable of performing strong encryption of its data. Once it has successfully authenticated a reader, changes to relevant data can be encrypted by the reader and written (back) to the tag. Permanent sensitive data can be also decrypted at the reader's side. But this requires efficient lightweight authentication protocols, and this area is likely to get further attention from researchers.

However, cryptography is no panacea. One basic reason, described in the second section, is the gap between ordinary computational devices (devices without stringent limitations on semiconductor area and power consumption) and weak processing devices. Thus noncryptographic solutions, as described in the previous section, may become more important.

It should be mentioned that no IS security and privacy can be fully exercised if there is no legal coverage. Although security and privacy related regulation is becoming broad and diverse, the RFID area has many specific issues that require tailored legislation. But this topic is outside the scope of this chapter.

CONCLUSION

A ubiquitous and pervasive computing paradigm is almost inherently tied to wireless communications. In addition, this paradigm rests on massive deployment of computing devices, which therefore have to be cheap. RFID technology is the special kind of such paradigm. Due to its specific properties it places further constraints on wireless security and privacy. These specific properties and available existing solutions have been discussed in detail in this chapter.

The majority of solutions that support security and privacy are built on cryptography, while some promising attempts are emerging that are not tied to cryptography (e.g., blocker tags, antenna-energy analysis, tag pseudonyms). Further, a new hybrid technique for tags authentication has been proposed that deploys the principles of tags pseudonyms and one-time passwords. It compensates the basic drawback of the pure tag pseudonyms approach, while the price to be paid (in terms of additional calculations and slightly prolonged response times) may be acceptable for many environments.

There is no doubt that RFID devices are about to become one kind of mainstream wireless technology. Currently being implemented mostly in supply chains and retail, their deployment possibilities are numerous, for example:

- Health care information systems can be improved for better handling of patients' data.
- Elderly and disabled people can benefit from new applications that are based on RFID.
- New applications for intelligent, smart-homes can be built on top of RFID.
- Scientific research of certain species can be improved, and so forth.

As for every technology, RFID technology has its advantages and disadvantages. To properly ensure security and privacy related measures, a proper risk management strategy has to be taken. Only the big picture of security and privacy assures to benefit from the use of this kind of wireless technology.

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KEY TERMS

Active Tag: A tag that has some source of energy, for example, a battery.

Kill Operation: Upon receipt of a certain communication primitive a tag becomes permanently blocked, for example, by blowing a fuse in its circuitry.

Passive Tag: A tag that is powered through electromagnetic coupling and obtains power from the reader.

Reader: A device that queries tags to obtain their IDs and that is connected to the back-end part of information systems.

RFID Technology: Wireless identification technology that operates in radio frequencies and deploys low-cost ICs.

Security Mechanism: A basis for a security service, where using a particular security mechanism (e.g., cryptographic algorithm) enables the implementation of security service.

Security Service: A service provided by an entity to ensure adequate security of data or systems in terms of authentication, confidentiality, integrity, and nonrepudiation.

Singulation: A process (an algorithm) that enables isolation and identification of a single tag.

Tag: A small, low cost IC with unique ID and computational capabilities to support identification processes.

Tag's Identity (ID): This is a unique number for each tag that is stored in silicon with imprinting process.

Wireless Security: Minimization of vulnerabilities of assets and resources when communicating information in electromagnetic media through a free-space environment.

Chapter XLVI
Security and Privacy Approaches for Wireless Local and Metropolitan Area Networks (LANs & MANs)

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ABSTRACT

Wireless communications are becoming ubiquitous in homes, offices, and enterprises with the popular IEEE 802.11 wireless local area network (LAN) technology and the up-and-coming IEEE 802.16 wireless metropolitan area networks (MAN) technology. The wireless nature of communications defined in these standards makes it possible for an attacker to snoop on confidential communications or modify them to gain access to home or enterprise networks much more easily than with wired networks. Wireless devices generally try to reduce computation overhead to conserve power and communication overhead to conserve spectrum and battery power. Due to these considerations, the original security designs in wireless LANs and MANs used smaller keys, weak message integrity protocols, weak or one-way authentication protocols, and so forth. As wireless networks became popular, the security threats were also highlighted to caution users. A security protocol redesign followed first in wireless LANs and then in wireless MANs. This chapter discusses the security threats and requirements in wireless LANs and wireless MANs, with a discussion on what the original designs missed and how they were corrected in the new protocols. It highlights the features of the current wireless LAN and MAN security protocols and explains the caveats and discusses open issues. Our aim is to provide the reader with a single source of information on security threats and requirements, authentication technologies, security encapsulation, and key management protocols relevant to wireless LANs and MANs.

INTRODUCTION

The topic of this chapter is the security of 802.11 wireless local area networks (WLANs) and of 802.16 wireless metropolitan area networks (WMANs). These networks are based on the IEEE standards belonging to the 802 family, which include the much-beloved Ethernet (802.3) that is common today in homes and offices. Although the development of the 802.11 technology and standards have been ongoing sine the late 1990s, grassroots adoption of "wireless Ethernet" only began in the 2000-2001 timeframe when access point (AP) devices became cheap enough for the home user to obtain.

The convenience of having wireless access to the IP Internet is self-evident. The value proposition in terms of employee productivity has been so compelling that many enterprises began also to introduce the technology into their corporate networks. This enterprise adoption, however, was prematurely halted when security flaws in the wired equivalency privacy (WEP) algorithm were discovered and published. Various temporary patches were then suggested in order to support existing enterprise investments in WLAN equipment, with the IPsec-VPN (e.g., over the wireless segment) as the most common approach. The IEEE standards community completed the revision of the security-related components of 802.11 in 2004, with conforming products scheduled to be shipped in 2005.

This chapter is not a user guide to specific WLAN or WMAN products, and intentionally avoids specific references to such products. It is also not a thesis on the various engineering solutions that could have been applied to solve the Wi-Fi security problem. Instead, the chapter attempts to explain what current approaches and solutions have been adopted, and why these were chosen.

The contents of the chapter are arranged in four parts, where each part groups together topics and issues that are closely related. These parts roughly cover the topics of WLAN authentication and authorization, WLAN security algorithms and protocols, security in WLAN roaming, and security in WMANs. These are described in more detail next.

BACKGROUND

Traditionally, the term *authentication* in the context of computer and network security concerns the ability of a verifier (or prover) entity to ascertain the correct *identity* of another entity claiming to be that identity. Thus, the aim of authentication is for one entity to prove its identity to another based on some *credentials* possessed by that first entity. Examples of credentials include passwords, digital certificates, or even physical keys. The outcome of an authentication process is typically binary, namely success or fail. The process is typically defined and implemented as one or more *protocols*.

The term *authorization* pertains to the rights, privileges, or permissions given to an authenticated entity in relation to some set of resources. In practice, authorization for an entity to take actions (e.g., access network, read files) is preconditioned on a successful authentication. The functions of authentication and authorization are often accompanied by *accounting* (or auditing), with the three loosely referred to as *AAA*.

The level of authorization assigned to an entity when it seeks access to resources is often tied to the type and strength of the authentication protocol used and the type of credential possessed by the authenticated entity. Hence, differing levels of assurance or certainty regarding the outcome of an authentication process can be gained by using different credentials and authentication protocols.

For example, when a password (as a credential) is used with a weak protocol (e.g., plaintext challenge-response), then a low or weak level assurance is obtained as both the credential and the authentication protocol are weak. In contrast, a strong credential such as a digital certificate when combined with a strong authentication protocol, such as SSL or transport layer security (TLS), achieves a higher level of assurance regarding the identity of the authenticated entity.

In today's complex computer and network systems, multiple credentials might be needed for an entity to access multiple resources, each access instance of which may be governed by separate sets of privileges. Thus, often the term *layer* (of

authentication and authorization processes) is used to describe complex situations.

One of the earliest questions with regards to authenticating dial-up users was how to run an authentication protocol with a (dial-up) client when it did not yet have an assigned IP address. This issue was of particular concern since the assignment of an IP address was subject to a successful authentication. However, most of the existing authentication protocols, such as IKE or SSL, were designed to be run over the IP layer with the end points possessing known source/destination IP addresses. This apparent chicken-and-egg problem was solved with the introduction of the extensible authentication protocol (EAP), first published as an Internet standard in 1998 in RFC2284 and more recently revised in RFC3748 (2004).

In the last couple of years EAP has come to the forefront of discussions, this time on 802.11 WLAN security and 802.1X. This is due to the similarity of the chicken-and-egg problem found in WLANs, namely the question of how a server on an IP network can authenticate an 802.IX supplicant when that supplicant does not yet have an IP address, and whose IP address assigned is in fact subject to a successful authentication by the server.

For the purposes of WLAN security EAP itself can be viewed as a framework within which a security protocol must be instantiated "inside" (on top of) EAP. Thus, with the emergence of EAP came the definition of a number of *EAP methods* which load EAP with the appropriate security protocol. One important EAP method is EAP-TLS, which is an instantiation of the TLS (or SSL) protocol inside EAP. More stringent that plain TLS in terms of certificate usage, EAP-TLS mandates the use of digital certificates at both the client and server side.

SECURITY ISSUES IN WIRELESS LANS AND MANS

Wireless networks make it easy for an attacker to read, modify, or drop packets, as the attacker often needs only to be in the vicinity of the communicating entities. In contrast, an adversary may need to gain entry to a physical access controlled building, wiring closet, or a network device to attack a wired network. The IEEE 802.11 standard attempts to emulate the physical attributes of wired medium in designing the WEP suite of security protocols and data transforms.

WEP consists mainly of an entity authentication protocol and a data security transform. The authentication protocol has two modes: open-system and shared-key authentication subtypes. The open-system authentication protocol is a 2-way handshake initiated by the entity requesting service. It consists of the requester asserting its identity and the responder returning with "successful" or "unsuccessful" only on the basis of whether open-system authentication is supported or not. In other words, open-system authentication protocol does not provide any security whatsoever. The shared-key protocol is a 4-way exchange, also initiated by the entity requesting service. It consists of request, challenge, challenge-response, and result messages in that order. The responder challenges the requester to provide proof of possession of the shared secret. The requester encapsulates the challenge-response message using the WEP transform to prove that it knows the WEP secret key. The responder decapsulates the message using its local copy of the shared secret key and compares the decrypted text with the original challenge text. If there is a match, the requester is granted a connection.

The data security transform, comprising the WEP encapsulation and decapsulation processes, is the other component of an 802.11 security solution. The standard recommends that the authentication protocol be used in conjunction with the data security transform.

WEP uses RC4 (Ron's code: a proprietary stream cipher designed by Ron Rivest of RSA Labs and later released into public domain) as the cipher to protect 802.11 frames. The WEP encapsulation process is designed to be "reasonably strong," self-synchronizing (considering that medium access control [MAC] protocol data units [MPDUs] may be dropped or arrive out of order, the receiving entity must be able to decapsulate an MPDU independent of prior or future MPDUs), efficient,

and easy to implement in hardware or software. Thus, an initialization vector (IV) for the RC4 cipher accompanies each MPDU, along with a key ID (shared-key ID used to encapsulate the current MPDU), and an integrity checksum to protect against MPDU modification en route. Briefly, the key and the IV are input to the RC4 encryption algorithm to generate a pseudorandom key stream for MPDU encapsulation. A checksum is computed over the MPDU using cyclic redundancy check (CRC-32) for integrity protection. The checksum is then appended to the MPDU and is XORed with the keystream to generate the ciphertext. WEP decapsulation follows the reverse process, where, upon decryption of an MPDU, the received checksum is compared with the locally computed checksum to verify the MPDU's integrity.

WEP design contains several well-publicized flaws. The nature of the flaws will be clear as we delve into the design details. The design goals themselves are suspect: the stated goal is wired equivalency privacy, which in itself is hard to capture. The choice of cipher, and especially the use of a stream cipher for encapsulating packets, also makes it easy for an attacker to cryptanalyze WEP encapsulated MPDUs. The choice of integrity algorithm, CRC-32, which is linear, makes it easy for an attacker to modify encrypted MPDUs without the receiver being able to verify whether the packets are legitimate or not.

Wireless LAN devices or wireless stations (STA) are considered as logically external entities to an enterprise network. Radio frequency (RF) waves in most deployment scenarios do not have physical boundaries and thus STAs should be allowed to access the corporate network only after going through a similar authentication procedure as in the case of remote access. For remote access, enterprises typically use IPsec for general purpose access to their intranets, and SSL for access to e-mail and other similar applications. In both cases, remote access servers and clients mutually authenticate each other, and arrive at a common security association (SA). Use of keys within that SA is proof of authentication for accessing the enterprise intranet via the remote access server.

STAs establish a robust security network association (RSNA) with an AP using IEEE 802.1X and EAP for authentication and key distribution. From the resulting master key, the AP and the STA engage in a 4-way exchange to derive session keys. STAs can only communicate to other entities in the wired or wireless network via an authenticated secure channel (using CCMP or TKIP as the security protocols). Thus, an AP enforces access control to the wired network and provides a means for authenticated and confidential communication between the STA and other entities in the network.

The primary reason WLANs were developed was to allow untethered connections between a client and an 802.11 access point (AP), as a basis for further access to resources and services on the Internet. The next step in this process is wireless roaming, in which a client can move across multiple APs in one administrative domain and across multiple APs across differing administrative domains. Currently, the most prevalent model for wired roaming consists of a dial-up connection from a client (e.g., a laptop) through an Internet service provider (ISP), to a home domain (e.g., corporate network). This model presumes the prior existence of a business relationship between the client (or its corporation) and one or more ISPs.

The term *Wi-Fi roaming* can be loosely defined as the set of services supporting the deployment and management of 802.11 WLAN access at public venues or public *hotspots*, where the customer of one service provider can obtain services (e.g., IP connectivity) from a different (visited) service provider. The term *service provider* (SP) here is intentionally left abstract since in today's Internet a number of entities can take the role of providing one or more services relating to Wi-Fi roaming. It is important to note that Wi-Fi roaming involves the crossing of both network-administrative boundaries and security-administrative boundaries. Therefore, on-campus WLAN access at different remote locations (e.g., offices, buildings) under the same administrative jurisdiction is not considered here as Wi-Fi roaming.

The business case for Wi-Fi roaming is self-evident: consumers with laptops or handheld devices are willing to pay for IP connectivity through

hotspots located throughout the world, provided that Wi-Fi access is easy to use and secure.

This desire is already true today, as seen in the case of dial up IP services. Many traditional ISPs see Wi-Fi roaming as providing a new business opportunity, by extending their edge services to a new kind of access point, namely, the public hotspot, while retaining as much as possible their investment in their existing backend authentication, authorization, and accounting (AAA) infrastructure.

For some *mobile network operators* (MNO) and carriers, the case for Wi-Fi roaming can even be considered imperative, as they are seeking to augment and extend existing mobile-related services to their customers at affordable prices. Mobile handsets that can make use of Wii hotspots—with speeds of 11 to 50 Mbps—could generate new business opportunities by providing users with higher-quality content and a higher level of interactivity. The case for Wi-Fi roaming is of particular interest to MNOs that have invested heavily in the recent acquisition of three-generation (3G) licenses.

Given the increasing mobility of the workforce, providing *secure* Wi-Fi roaming is an important challenge today. Corporations see remote access as a given fact of life and expect services from their ISPs supporting remote access. This is true in dial-up today, and it is something expected of Wi-Fi roaming in the near future.

Wi-Fi roaming has recently taken an interesting direction in North America due to the entrance of a number of MNO into this space. These MNOs want to enhance their 2G and 2.5G (and later their 3G) offerings with Wi-Fi related services. Many MNOs already perceive that in practice a universal mobile telecommunications system (UMTS) may not reach its theoretical data rates of 2 Mbps. Thus, Wi-Fi at hotspots—with speeds of up to 11 Mbps in 802.1lb and up to 54 Mbps in 802.1la—may provide a solution for the need for higher data rates complementing their 2.5G and 3G offerings. From a content perspective, the marriage of GSM/UMTS and Wi-Fi roaming makes very good sense. The ability of 802.11 Wi-Fi hotspots to provide high-speed connectivity to the Internet makes it attractive for downloading richer content for mobile devices (e.g., PDAs and GSM phones) beyond the ring tones of today. Such content may include MP3 music files, interactive online games, and MPEG4 video clips, depending on the capabilities of the device.

The authentication protocol used in GSM has been the *subscriber identity module* (SIM), while for UMTS it will be *UMTS subscriber identity module* (USIM). Both take the physical form of a *universal integrated circuit card* (UICC), with the next generation based on tamperproof smartcard technology. In the context of 3G-WLAN roaming, the proposed protocols (EAP methods) for authentication are EAP-SIM for SIM-based users and EAP- authentication and key agreement (AKA) for USIM-based users.

The choice of the SIM and AKA methods for authentication has been dictated by the need of the MNOs to keep as much as possible their back-end AAA infrastructure unmodified for Wi-Fi usage. However, since the SIM and AKA protocol were designed for GSM/UMTS networks, they are not transferable to the IP world without introducing some vulnerabilities. Thus, the "naked" SIM or AKA exchange needs protection while in the IP segment of the end-to-end handshake between the SIM/USIM card (in the UE) and the HLR/HSS at the home network. One possible solution around this problem is to wrap the SIM/AKA exchange within a TLS layer, which can be done by layering the SIM or AKA handshake above (wrapped within) protected extensible authentication protocol (PEAP) or tunneled TLS (TTLS).

However, in addition to these issues that are specific to EAP-SIM and EAP-AKA, the 3GPP-WLAN interworking security specifications have also outlined a number of other issues and requirements. Some of these are as follows:

- **Mutual authentication:** In addition to the user authenticating itself to the home network, the network must in turn authenticate itself to the user. The EAP-AKA protocol provides this feature.
- **Signaling and user data protection:** Subscribers should have at least the same security level for WLAN access as for their current cellular access subscription. This require-

ment translates to the need to protect their interfaces or connections between the Wi-Fi hotspot (namely, the WLAN access network) and the 3GPP network, between the 3GPP AAA proxy to the 3GPP AAA server, and between the 3GPP server and the HSS.
For the connection between the Wi-Fi hotspot and the 3GPP network, most likely the protocol used will be RADIUS or Diameter.

- **Identity privacy:** The user's privacy while roaming from one Wi-Fi hotspot in another needs to be guarded. That is, when the user is assigned a temporary identifier (or pseudonym), it should be infeasible for an attacker to reverse this process and correlate the pseudonym with the actual user identifier. Naturally, it should also be infeasible for an attacker to generate a valid pseudonym note that temporary identifiers can be used within EAP-AKA.
- **Protection of the interface between UIC and WLAN access devices:** Here, the concern relates to the wish of operators to reuse existing UICC and GSM SIM cards in laptops and PDAs, which may have different physical security measures than mobile handsets. Thus, the UE is perceived to possibly have a functional split implemented over several physical devices/components, where one device holds the UICC/SIM card, while another device provides WLAN access.

The interface across this functional split needs to be protected. There is little point in providing a near tamper-free UICC or SIM card, when the WLAN-access device at the user (e.g., radio circuitry or WLAN software/hardware) can be manipulated by an attacker to obtain PS from the home network or visited network, as these services are core to the business of MNOs.

The aim is to provide protection to the level where attacking the PS domain (in UMTS network) by compromising the WLAN access device is at least as difficult as attacking the PS domain by compromising the card-holding device.

It is for this reason that there is currently interest in providing EAP functionality on board the UICC, thereby achieving true end-to-end EAP-AKA (or EAP-SIM) exchange between the network and the UICC (instead of the laptop hosting the UICC).

The area of broadband Internet has gained a lot of interest in recent years due the exciting business opportunities enabled by high-speed Internet connectivity to homes and businesses. Content owners (e.g., movie studios and record labels) and content providers/distributors (e.g., music and MPEG4 download services) see broadband Internet to the home as crucial to providing the next source of revenue, as it solves the difficult "last mile access" problem. Thus, if "content is king" as the saying goes, last mile access is the "queen" that enables content to flow to the consumer.

Today, only a fraction of U.S. households have broadband Internet in the form of cable modem services or DSL services. The mid-2004 subscriber numbers indicate that there are just over 18 million subscribers to broadband Internet. This is due, among others, to the difficulty in installing cables for those services in dense areas with old buildings and infrastructures, despite the fact that the two technologies have reached maturity. Furthermore, in many areas in the United States consumers who do have cable modem services available are unable to choose among service providers because a virtual monopoly has been established by one (or two) provider(s). The opportunity to remedy the situation is somewhat better in countries that are still developing their physical infrastructures today since they are able to build broadband Internet into their infrastructure designs.

It is with this background that *wireless metropolitan area networks* based on the 802.16 technology have recently gained a lot of interest among vendors and ISPs as the possible next development in wireless IP offering and a possible solution for the last mile access problem. With the theoretical speed of up to 75 Mbps and with a range of several miles, 802.16 broadband wireless offers an alternative to cable modem and DSL, possibly displacing these technologies in the future.

Wireless MAN security architecture has two main design goals: to provide controlled access to the provider's network, and to provide confidentiality, message integrity protection, and replay

protection to the data being transmitted. WMAN communications can be one-to-one or one-to-many. In one-to-one communication, typically users are interested in protecting their data, and service providers in controlling access to their networks. In one-to-many communication, service or content providers encrypt data and provide keys to their subscribers; thus content access control is the only goal in this case.

For access control, one may use asymmetric (digital certificates) or symmetric (e.g., preshared keys, SIM cards) authentication methods; the revised 802.16 specification allows the use of either of these two classes of authentication methods. From a provider's perspective, an SS authenticating itself to a BS is sufficient for enforcing controlled access to the provider's network. However, for user data confidentiality, the one-way authentication is not sufficient. Consider, for example, that SS to BS authentication alone will not help detect an adversary claiming to be a BS and thereby launching a man-in-the-middle attack.

The revised IEEE 802.16 specifications update the cryptographic algorithms used for encryption and integrity protection, increase key lengths, and add replay protection. The revised key management protocol design consists of robust protection again replay attacks.

A few further additions to the 802.16 security architecture facilitate symmetric key-based authentication, and more importantly mobility. Specifically, a key hierarchy is defined for fast keying when a mobile SS (MS) associates with a new BS.

Controlled or metered access to the WMAN or any content disseminated via the WMAN is the foremost requirement of service providers. This basic requirement typically translates into many components.

First, any service provider's BS must be able to uniquely identify an MS that wants to get access to the network. The MS may identify itself to a BS using digital certificates or indirectly to a legacy authentication server (AS) (e.g., AAA server) in conjunction with a symmetric authentication method. In the latter case, the MS does not need to perform expensive computations as would be the case with digital certificates. Furthermore, in most cases, the BS only forwards authentication protocol messages to the backend AS for authentication. After verifying the MS's credentials, the AS informs the BS of the result—authentication success or failure—and securely transfers the master session key (MSK).

The second component of enforcing access control is key distribution. The BS must be able to uniquely and easily identify packets from authorized MSs so it can enforce authorized access to the WMAN. Thus, after successfully authenticating an MS, the BS establishes a secret key with the MS. The MS must include a proof of possession of the secret key with each packet. The most common way to achieve this is to compute a cryptographic integrity checksum with each packet, and include it with the packet. In WMANs, the BS and MS may derive the keying material as part of the authentication protocol, or the BS may supply the key(s) to the MS.

Third, the IEEE 802.16 specification defines a multicast and broadcast service (MBS). This allows WMAN service providers to distribute content efficiently via multicast to relevant subscribers. The provider enforces controlled access to the content by distributing a per-group secret key to the subscribers who paid for the additional services.

In addition to covering service providers' requirements, the security sublayer addresses WMAN users' requirements. User requirements are typically to protect the confidentiality and integrity of the data. In simpler terms, users want to ensure that a third party cannot read their communications, their data are not modified en route, and that no one injects or drops packets without being detected. It is quite difficult, if not impossible, to protect against an adversary dropping packets; the other requirements are fairly easy to achieve and the 802.16 standard specifies how to in the WMAN context. Specifically, in addition to encryption, WMAN secure encapsulation provides per-MPDU integrity protection as well as replay protection.

Within the extended security sublayer there are two versions of the PKM protocol: version 1 is quite similar to the basic security sublayer, except

that it supports new ciphers including 3DES-ECB and AES-ECB for confidentiality of key material, and AES-CCM for MPDU confidentiality. HMAC-SHA-1 protects the integrity of the key management messages. PKMv2 comparatively has many more desirable properties, including mutual authentication using various combinations of RSA-based and EAP-based authentication protocols, additional message integrity algorithms, and key management protocols.

Before we delve into that discussion, a bit of context of the design motivation for PKMv2 is in order. PKMv2 is part of a specification to add mobility extensions to the base 802.16 standard. When MSs are mobile, it may be desirable that they preauthenticate with a BS they plan to associate with, to reduce any potential for interruption in service, be it access to the provider's network, or a-multicast/broadcast content delivery service. Thus preauthentication is one of the additional features in PKMv2. Similarly a key hierarchy is defined to allow an MS to authenticate itself to the backend AAA server once, irrespective of any number of BSs it may associate with. Along with these extensions for mobility, the new specification includes several enhancements to the WMAN security protocols. In the rest of this chapter, we discuss these additional features and their advantages and shortcomings.

EAP-based mutual authorization in PKMv2 alone can support mutual authentication (indirect mutual authentication via a proof of possession of a key, if a back end AS is involved). However, a combination of RSA authorization followed by an EAP authentication may also be used in WMAN access. In that case, the RSA authorization is considered to provide device mutual authentication, whereas the EAP authentication is user authentication (which is especially true if a SIM card is involved in authentication).

EAP authentication in PKMv2 is similar to that in the 802.1 X/EAP-based authentication of 802.11i STAs: the MS authenticates to an AS via an authenticator. The BS in 802.16 networks serves as the authenticator, although in some architectures the functionality of the authenticator and the BS might be separated (this model of separating the BS and the authenticator needs a further review before being considered secure). EAP authentication follows the steps below:

- The authenticator or the BS initiates the EAP authentication process. Note that in the public-key-based authentication protocol, the MS requests authentication. The BS sends an EAP request message to the MS. This is typically an EAP identity request encapsulated in MAC management protocol data unit (PDU) (i.e., the secondary management channel carries the EAP messages).
- The MS responds to the request with an EAP response message. The authenticator and the MS continue the EAP exchanges until the authentication server determines whether the exchange is a failure or a success. The exact number of the EAP messages depends on the method used for authentication.
- An EAP success or an EAP failure terminates the EAP authentication and authorization process. At the end of the protocol run, the BS and the MS have the primary master key (PMK).

If the EAP exchange follows and RSA authorization exchange, the EAP messages are protected using the EAP integrity key (EIK) derived as a result of the RSA authorization exchange. The EAP messages contain an AK sequence number (the AK and the EIK are derived from the RSA exchange) for replay protection and an OMAC digest, computed using the EIK, for integrity protection.

If a backend AS is involved in the EAP authentication process, the AS delivers the PMK to the authenticator or the BS after the EAP exchange is complete. The BS and the MS then engage in a 3-way exchange to prove to each other that they possess the PMK. The 3-way exchange can be run several times under the protection of the PMK to amortize the cost of the EAP authentication exchange.

IMPLEMENTATION ISSUES

IEEE 802 standards committee formed the 802.11 Wireless Local Area Networks (WLAN) Standards

Working Group in 1990. IEEE 802.11 standard does not provide technology or implementation, but introduces the specifications for the physical and the MAC layers. 802.11 is the wireless protocol for both ad hoc and client/server networks. The users' acceptance of this protocol is high. Although, the security of the transmission channel is a matter of special attention that always has to be considered.

The WEP scheme has been adopted by IEEE 802.11 standard to ensure security for the transmitted information. The basic two components of WEP are the pseudorandom number generator (PRNG) and the integrity algorithm. The PRNG is the most valuable component because it actually is the original encryption core. WEP adopts RC4 cipher as the PRNG unit and CRC-32 as the integrity algorithm. Although WEP is a good security scheme, the offered security in some cases can not satisfy the user demands. In order a higher security level to be ensured, 802.11i working group introduced, as protocol's security scheme, the advanced encryption standard (AES).

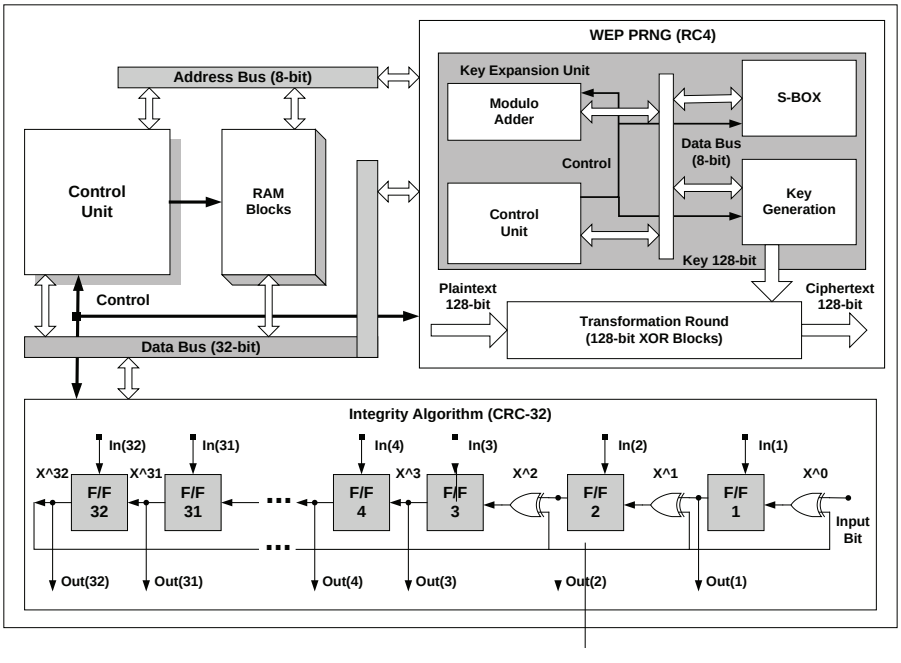
In this section the hardware implementation cost of both WEP and AES schemes is presented. In order to have a fair and detailed comparison between the two schemes, the same implementation platform has been used (i.e., the same field programmable gate array [FPGA] device).

For the AES scheme, a compact VLSI architecture is presented. The implementation of this architecture minimizes the allocated area resources. The area-optimized design does not sacrifice the system performance in a restricted way. The throughput of the design is much higher than the required by the IEEE 802.11 standard. Both WEP and AES schemes are compared in terms of implementation performance: allocated area resources, operating frequency, throughput, and power consumption. Aspects of the supported security of these encryption schemes are discussed and security level strength comparisons are given.

The proposed architecture for the implementation of the WEP scheme is illustrated in Figure 1.

In order to implement in hardware the cyclic redundancy check (CRC-32), a shift register of 32 flip-flops (F/Fs) and a number of XOR gates are used. So, a linear feedback shift register (LFSR) design is produced by using the F/Fs chain with

Figure 1. WEP scheme architecture



the XOR gates. The characteristic polynomial of this LFSR is:

$$(X) = X^{32}+X^{26}+X^{23}+X^{22}+X^{16}+X^{12}+X^{11}+X^{10}+X^{8}+X^{7}+X^{5}+X^{4}+X^{2}+X+1$$

The presence/absence of an XOR gate in CRC-32 architecture corresponds to the presence/absence of a term in G(X) polynomial. The required output message is the content of the LFSR after the input message last bit is sampled.

RC4 is a variable key-size stream cipher and operates on one plaintext block at a time. RC4 architecture consists of the key expansion unit and the transformation round. The key expansion unit is mainly a S-Box component. For the S-BOX implementation a 256-byte RAM memory block is used and another similar memory block is needed for the key array. The transformation round is a simple bit-by-bit XOR between the plaintext and the key.

IEEE 802.111 and Advanced Encryption Standard (AES)

AES proposed architecture operates in counter mode with cipher block chaining–message authentication code (CCMP). According to IEEE 802.11i working group, this operation mode is used to ensure, at the same time, integrity and privacy. The proposed AES architecture is shown in Figure 2.

The AES scheme architecture operates each time on a column of 32-bit data. It needs 41 clock cycles to complete the transformation of a 128-bit plaintext block. The column subunit is composed of four basic building blocks: S-Box, DataShift, MixColumn, and KeyAddition. The RAM-based design for the S-BOXes ([256x8]-bit) guarantees high performance. This "column"-based architecture minimizes the area resources compared with "state"-based architectures.

Figure 2. Advanced encryption standard (AES) scheme architecture

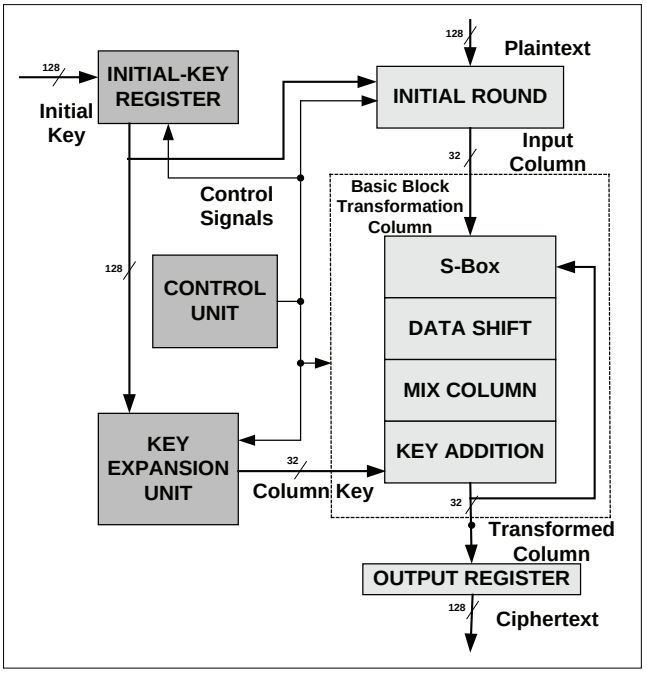
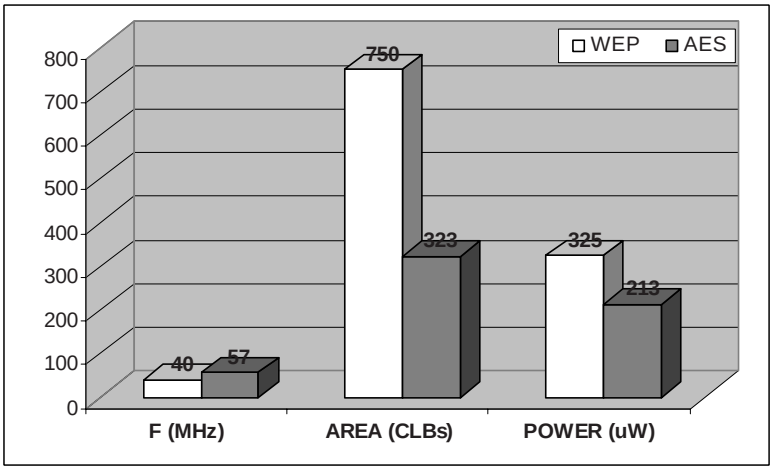


Figure 3. Implementations comparisons



Implementation Cost and Performance Evaluation

In Figure 3, the synthesis results for both WEP and AES implementations are illustrated. For the hardware integration the FPGA device Xilinx Virtex (2V250fg256) (2003) has been used. For power consumption estimation, the Xilinx tool was used.

Based on the synthesis results regarding the area resources, the utilization of both implementations are: AES, 323 CLBs (allocated) + 1213 CLBs (unused) = 1526 CLBs (available in the FPGA device), and for WEP, 750 CLBs (allocated) + 776 CLBs (unused) = 1526 CLBs (available in the FPGA device). The AES implementation performs better compared with WEP implementation. The minimized area resources of AES do not sacrifice the system performance, which reaches throughput value 177 Mbps. On the other hand, RC4 is a more "heavy" design for mobile devices hardware implementation. This is due to the specified S-Boxes and the key expansion unit specifications. RC4 performance is the bottleneck for WEP throughput which reaches the value of 2.22 Mbps. The main RC4 implementation disadvantages, compared with AES, are: (1) more required silicon area resources, (2) higher power consumption, and (3) lower operating frequency. Concluding and based on the above comparison results, the proposed AES implementation is proposed for applications with special needs in both area resources and operation frequency.

Concerning security aspects, AES offers, at the same time, privacy and integrity. On the contrary, WEP scheme needs two different algorithms in order to support bulk encryption and data integrity. In some cases, where AES security is unbreakable, WEP security could be broken. These comparisons give AES advantages and make it an efficient and trustworthy solution for the next years' IEEE 802.11 networks.

CONCLUSION AND OUTLOOK

Generally speaking, the entire field of the "wireless Internet"—namely, wireless connectivity to the IP network—is still relatively new and may take a few more years to reach the level of ubiquity comparable to other access technologies such as dial-up over PSTN. What is evident, however, is that user mobility is a crucial aspect of the next

generation Internet services where the ordinary user will expect connectivity to be something that is permanently available, much like electricity that is "always on."

There are a number of emerging technological trends today that may influence the future of WLANs and WMANs. We summarize these in the following and describe possible outcomes and developments in this exciting field.

- **The transparent "always on" Internet:** Increasingly the details of the operations of the IP Internet will become transparent or removed from the ordinary user. In the past, many early-home adopters of WLANs have had to familiarize themselves with important IP networking concepts (such as IP addresses, ports on switches/routers, and so forth) in order to set-up a home WLAN. Today, through improved quality and ease of use of WLAN products, most products are essentially plug-and-play. This human aspect is important because it contributes to the user's expectations of an always-on Internet, whether they access it from a home WLAN, a Wi-Fi hotspot, a wireless broadband (WMAN) provider, or from a 3G/GPRS provider. Increasingly, the lay user will not care how connectivity is provided, but will expect high-bandwidth connectivity to be ubiquitous. This expectation will in turn influence how service providers establish seamless services between the IP Internet and the 2G/3G mobile networks.
- **Increased adoption of 802.1X:** The 802.1X approach for WLAN authentication is increasingly being adopted by enterprises, due in part to its support within the Microsoft Windows family of products. Although various networking vendors have been touting proprietary security products for WLAN authentication, the completion of the revision to the IEEE 802.1X standard together with recent progress in the Internet Engineering Task Force (IETF) on EAP-related standards should lead to the strengthening of 802.1X in the market. In the context of Wi-Fi roaming, technically 802.1X provides better security than the UAM Web-based approach. Thus, one possible development is for MNOs to also begin adopting 802. IX for their Wi-Fi hotspots, possibly reusing their SIM-based authentication with 802.IX (e.g., using an EAP method such as EAP-SIM).
- **Enterprise adoption of "IPsec everywhere":** Many enterprises who were early adopters of intracampus WLANs solved the 802.11 WEP security problem by running IPsec connections internally within the enterprise network. Although the "IPsec everywhere" approach was initially promoted as a temporary patch over the insecure WLAN segment of the network, increasingly some enterprises have continued to use IPsec for other purposes (e.g., establish virtual LANs). There are a number of possible consequences—intended or unintended—of using IPsec in this manner.

One possible effect of the widespread use of IPsec within internal corporate networks—both LANs and WLANs—is to bring the connectivity layer one step higher, introducing a new *IPsec layer* in the stack. Thus, here IPsec could be seen as the network layer transport (instead of the plain IP at ISO/OSI layer 3), where the actual IP addresses of the endpoints become less important than the identity and IPsec credentials (e.g., digital certificates or shared secrets) of those endpoints. This deemphasizing of the IP layer and increased focus on the IPsec layer may force networking hardware vendors to introduce richer security functionality into their hardware. Examples would be routers that can route based not only on IP addresses, but also on other characteristics of the IPsec connection (e.g., IKE and IPsec security associations).

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KEY TERMS

Access Point (AP): The network access device for an 802.11 wireless network. It contains a radio receiver/transmitter. It may be an 802.1x authenticator.

Certification Authority (CA): An entity that issues digital certificates (especially X.509 certificates) and vouches for the binding between the data items in a certificate.

Extensible Authentication Protocol (EAP): A protocol used between a user station and an authenticator or authentication server. It acts as a transport for authentication methods or types. It in turn may be encapsulated in other protocols, such as 802.1x and RADIUS.

EAP-AKA: This document specifies an extensible authentication protocol (EAP) mechanism for

authentication and session key distribution using the authentication and key agreement (AKA) mechanism used in the 3rd generation mobile networks universal mobile telecommunications system (UMTS) and CDMA2000. AKA is based on symmetric keys, and runs typically in a subscriber identity module (UMTS subscriber identity module [USIM], or removable user identity module [RUIM], a smart card like device).

EAP-LEAP: Lightweight extensible authentication protocol is a Cisco proprietary EAPType. It is designed to overcome some basic wireless authentication concerns through mutual authentication and the use of dynamic WEP keys.

EAP-PEAP: Protected extensible authentication protocol is a two-phase authentication like EAP-TLS. In the first phase the authentication server is authenticated to the supplicant using an X.509 certificate. Using TLS, a secure channel is established through which any other EAP-Type can be used to authenticate the supplicant to the authentication server during the second phase. A certificate is only required at the authentication server. EAP-PEAP also supports identity hiding where the authenticator is only aware of the anonymous username used to establish the TLS channel during the first phase but not the individual user authenticated during the second phase.

EAP-SIM: EAP-SIM is an authentication mechanism that makes use of the SIM card to perform authentication within the 802.1x framework for WLAN.

EAP-TLS: Transport layer security is an EAP-Type for authentication based upon X.509 certificates. Because it requires both the supplicant and the authentication server to have certificates, it provides explicit mutual authentication and is resilient to man-in-the-middle attacks. After successful authentication a secure TLS link is established to securely communicate a unique session key from the authentication server to the authenticator. Because X.509 certificates are required on the supplicant, EAP-TLS presents significant management complexities.

EAP-TTLS: Tunneled TLS is an EAP-type for authentication that employs a two-phase authentication process. In the first phase the authentication server is authenticated to the supplicant using an X.509 certificate. Using TLS, a secure channel is established through which the supplicant can be authenticated to the authentication server using legacy PPP authentication protocols such as PAP, CHAP, and MS-CHAP. EAP-TTLS has the advantage over EAP-TLS that it only requires a certificate at the authentication server. It also makes possible forwarding of Supplicant requests to a legacy RADIUS server. EAP-TTLS also supports identity hiding where the authenticator is only aware of the anonymous username used to establish the TLS channel during the first phase but not the individual user authenticated during the second phase.

European Telecommunications Standards Institute (ETSI): ETSI is a multinational standardization body with regulatory and standardization authority over much of Europe. GSM standardization took place under the auspices of ETSI. ETSI has taken the lead role in standardizing a wireless LAN technology competing with 802.11 called the high performance radio LAN (HIPERLAN).

Integrity Check Value (ICV): The checksum calculated over a frame before encryption by WEP. The ICV is designed to protect a frame against tampering by allowing a receiver to detect alterations to the frame. Unfortunately, WEP uses a flawed algorithm to generate the ICV, which robs WEP of a great deal of tamperresistance.

Institute of Electrical and Electronics Engineers (IEEE): A worldwide professional association for electrical and electronics engineers that sets standards for telecommunications and computing applications.

Initialization Vector (IV): Generally used as a term for exposed keying material in cryptographic headers; most often used with block ciphers. WEP exposes 24 bits of the secret key to the world in the frame header, even though WEP is based on a stream cipher.

Medium Access Control (MAC): The function in IEEE networks that arbitrates use of the network capacity and determines which stations are allowed to use the medium for transmission.

MPDU: MAC protocol data unit is a fancy name for frame. The MPDU does not, however, include PLCP headers.

MSDU: MAC service data unit is the data accepted by the MAC for delivery to another MAC on the network. MSDUs are composed of higher-level data only. For example, an 802.11 management frame does not contain an MSDU.

OFDM: Orthogonal frequency division multiplexing is a technique that splits a wide frequency band into a number of narrow frequency bands and inverse multiplexes data across the subchannels. Both 802.11a and the forthcoming 802.11g standards are based on OFDM.

Open Systems Interconnection (OSI): A baroque compendium of networking standards that was never implemented because IP networks actually existed.

Request for Comments (RFC): A series of numbered documents (RFC 822, RFC 1123, etc.), developed by the Internet Engineering Task Force (IETF) that set standards and are voluntarily followed by many makers of software in the Internet community.

Wireless Application Protocol (WAP): A standard for providing cellular telephones, pagers, and other handheld devices with secure access to e-mail and text-based Web pages. Introduced in 1997 by Phone.com, Ericsson, Motorola, and Nokia, WAP provides a complete environment for wireless applications that includes a wireless counterpart of TCP/IP and a framework for telephony integration, such as call control and telephone book access. WAP features the wireless markup language (WML), which was derived from Phone.com's HDML and is a streamlined version of HTML for small-screen displays. It also uses WMLScript, a compact JavaScript-like language that runs in limited memory. WAP also supports handheld input methods, such as a keypad and voice recognition. Independent of the air interface, WAP runs over all the major wireless networks in place now and in the future. It is also device-independent, requiring only a minimum functionality in the unit to permit use with a myriad of telephones and handheld devices.

Chapter XLVII
End-to-End (E2E) Security Approach in WiMAX:
A Security Technical Overview for Corporate Multimedia Applications

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ABSTRACT

An overview of the technical and business aspects is given for the corporate deployment of services over worldwide interoperability for microwave access (WiMAX). WiMAX is considered to be a strong candidate for the next generation of broadband wireless access; therefore its security is critical. This chapter provides an overview of the inherent and complementary benefits of broadband deployment over a long haul wireless pipe, such as WiMAX. In addition, we explore end-to-end (E2E) security structures necessary to launch secure business and consumer class services. The main focus of this chapter is to look for a best security practice to achieve E2E security in both vertical and horizontal markets. The E2E security practices will ensure complete coverage of the entire link from the client (user) to the server. This is also applicable to wireless virtual private network (VPN) applications where the tunneling mechanism between the client and the server ensures complete privacy and security for all users. The same idea for E2E security is applied to client-server-based multimedia applications, such as in Internet protocol (IP) multimedia subsystem (IMS) and voice over IP (VoIP) where secure client/server communication is required. In general, we believe that WiMAX provides the opportunity for a new class of high data rate symmetric services. Such services will require E2E security schemes to ensure risk-free high data-rate uploads and downloads of multimedia applications. WiMAX provides the capability for embedded security functions through the 802.16 security architecture standards. IEEE 802.16 is further subcategorized as

802.16d (fixed-WiMAX) and 802.16e (mobile-WiMAX). Due to the mobility and roaming capabilities in 802.16e and the fact that the medium of signal transmission is accessible to everyone, there are a few extra security considerations applied to 802.16e. These extra features include: privacy key management version 2 (PKMv2), PKM-extensible authentication protocol (EAP) authentication method, advanced encryption standard (AES) encryption wrapping, and so forth. The common security features of 802.16d and 802.16e are discussed in this chapter, as well as the highlights of the security comparisons between other broadband access, third-generation (3G) technologies, and WiMAX.

INTRODUCTION

The E2E security structure is transparent from the user's point of view and requires dedicated overhead and processing power. In the case of Wi-Fi, the overhead is a relatively large percentage of the total bandwidth, which makes Wi-Fi infeasible for most E2E security structures. However, in worldwide interoperability for microwave access (WiMAX), the security overhead is nominal and may not be an issue.

Today's enterprise customers are forced to use dedicated physical circuits such as leased lines to realize business class E2E security. With inherent WiMAX security features, a secured virtual private network (VPN) can easily be achieved over public networks. Instead of such dedicated leased line circuits, WiMAX users could enjoy VPN connectivity with up to 10 Mbps bandwidth to access the public backbones.

Personal broadband access technologies have undergone many challenges, one of which was digital subscriber line (DSL). DSL is a high-speed connection that utilizes the same wiring system as a regular telephone line uses. The advantages of DSL include: voice/data on the same line and higher data rates than regular modems. There are, however, a few downsides to DSL, including distance dependence (between users and the service provider) of data rate, unbalance rates for uploading and downloading of data, and having no complete physical area coverage.

All of the downsides of DSL technology appear in other personal broadband products. This is due to the physical limitations of wired technologies. WiMAX, on the other hand, is a wireless technology with very high bandwidth for voice/data applications, which does not appear to have any of the downsides of the wired technologies. WiMAX also has advantages over Wi-Fi technology in terms of longer range and larger bandwidth. This allows WiMAX to support a variety of broadband services.

Wi-Fi technology was not suited for personal broadband services due to a number of limitations, especially security. WiMAX, on the other hand, enjoys an all-IP open platform infrastructure with the benefit of its inherent security functions and features. This allows for faster and inexpensive provisioning of E2E secured services based on open standards. In addition WiMAX can be configured for self-installed services of multimedia VPN with enhanced end-to-end user control signalling.

The security aspect of WiMAX is an important issue: this includes state-of-the-art security mechanisms, such as very strong authentication with per station keys and higher-level security mechanisms. WiMAX's security strength is normally found in add-on products, such as in wired VPNs and virtual local area networks (VLANs), which are usually built into each of the WiMAX's base stations (BSs).

This chapter will present the characteristics of WiMAX security and how it fits into both consumer and business class structures. We believe that strong E2E security can be achieved with WiMAX without compromising performance.

Why Wireless Networks Could not Provide the Required Security

There were two main reasons why wireless was never considered as a secured high-performance backbone option for business and corporate applications. The first issue was the bandwidth limitations of wireless links and the second issue was the high security requirements of VPNs and IMS applications. The 802.11-based systems have an upper limit on bandwidth of 54 Mbps for 802.11g, however in real-world applications, this rate seldom tops more than 20-25 Mbps due to the overhead in the medium access control (MAC) layer. It is also very difficult to have a minimum guaranteed bandwidth for real-time applications such as VoIP and videoconferencing.

The current Wi-Fi security standard is presented in 802.11i, which contains many fixes for the security concerns in 802.11. However 802.11i has not been widely implemented and distributed among end-users and WiMAX is expected to dominate the market before 802.11i can affect the market. Therefore the main security comparisons are between Wi-Fi (802.11a/g) and 802.16. The main reasons for this weakness can be categorized as follow (Gast, 2004):

Problem #1: Easy Access
Since Wi-Fi networks generate beacon frames containing the network parameters all of the time, attackers with high gain antennas can find networks and launch attacks. With the inherent and add-on security features, WiMAX is expected to be resilient against such attacks.

Problem #2: "Rogue" Access Points
Anyone can have access to an inexpensive access point (AP) and get connected to a corporate network and bypass authorization. In WiMAX networks, an E2E security scheme can protect APs against such a scenario.

Problem #3: Unauthorized Use of Service
Nearly all APs have default configurations with wired equivalent privacy (WEP) or with a default key used in WEP by all the vendor's products. Without WEP, a network can be accessed by any anyone. Even with WEP enabled, a network is not considered to be secure nowadays.

Problem #4: Performance and Service Constraints
802.11b and 802.11g both have limited transmission capacities (11 and 54 Mbps) and due to MAC-layer overhead, the actual effective throughput is close to half of that rate. In addition, bandwidth is not guaranteed.

Problem #5: MAC Spoofing and Session Hijacking
802.11 networks do not authenticate frames and there is no protection against a forgery of the frame source address attack. Here, attackers can use spoofed frames to redirect traffic and corrupt address resolution protocol (ARP) tables. Station MAC addresses could easily be observed and engaged in malicious transmissions. Any user with a strong transmitter can be situated in the middle of a new session and potentially steal credentials and gain access through a man-in-the-middle (MITM) attack.

Problem #6: Traffic Analysis and Eavesdropping
802.11 is totally vulnerable to passive attacks. There is no security of the header information, thus, no protection against eavesdropping. Frame headers are always "in the clear" and sender-receiver pairs are vulnerable to traffic analysis.

Problem #7: Higher Level Attacks
Once an attacker gains access (either through session-hijacking, MITM, spoofing attacks, or through breaking the WEP secure key), it is possible to use that AP to launch attacks on other systems, which are within the trusted domain of the initially attacked AP.

The main reason for the failure of security in wireless networks is the fact that there are many weaknesses in the mechanisms and protocols used in the architecture.

WIMAX SECURITY LAYERS

Transmission control protocol (TCP)/IP protocol stacks have currently dominated the data traffic transmitted between transmitters and receivers attached to the backbone of the Internet. The same situation also applies to WiMAX infrastructures, therefore it is vital to study the performance and security aspects of WiMAX systems in a similar layered fashion. In principle, communication systems are based on the seven-layer OSI model. However, most systems communicating on the Internet's backbone obey the five-layer architecture and WiMAX security protocol foundation is based on the lower-layers (e.g., the MAC layer), which provides extra capabilities in constructing security functions.

WiMAX enjoys the inherent security features with an open system platform, the all-IP structure, with options to enhance security in different layers of the WiMAX open architecture. All of these features have contributed to the strength of WiMAX security, which potentially enables secured applications such as VoIP and content streaming. The E2E security scheme also plays a vital role in adding an extra security feature to enable secure connections for seamless roaming for wireless broadband technologies across any network supporting TCP/IP.

This layered approach to security is further discussed in sections 3.1, 3.2, and 3.3.

Physical Layer Security

IEEE 802.16 is a MAC-layer-based protocol and its security schemes are mainly situated in the security sublayer of the MAC layer, where most of the algorithms and security mechanisms initially work. Here, physical (PHY) and MAC layers are closely related to one another. The basic security functions at the physical layer are in the form of key-exchange, encryption, and decryption. These mechanisms are however controlled at the MAC layer. Therefore the main objective of this section is to understand the MAC layer security mechanisms.

Another aspect related to the PHY layer is the transmission power. Unlicensed WiMAX has the same inherent security capabilities as compared to the licensed WiMAX. They do differ, however, in the amount of transmission power (unlicensed WiMAX carriers having a lower maximum power) which limits the range and also the possibility for interference.

Some other security implementations at the physical layer exploit the fact that modulation is done at this layer. Some transmitters may use frequency inversion as a security deterrent (Chandra, 2002). For example, the transmitter may divide the spectrum into various frequencies and use the different frequencies in a predetermined fashion. Obviously, this requires that both the sender and the receiver share a frequency hopping pattern. This is a form of spread spectrum communication.

Spread-spectrum systems also have an inherent security mechanism since data meant for a particular receiver, cannot easily be intercepted by other receivers if they do not possess the frequency hoping order which is controlled by the key.

Physical layer security implementations do not provide robust protection against attacks as they are prone to attacks such as the disruption of service (denial-of-service [DoS]). Other passive and active attacks include cross-connects and adjacent channel interference.

Therefore parts of the encryption/decryption mechanisms (which are mainly controlled at the MAC layer) that deal with the physical act of hiding information from the intruders' eyes are part of the PHY layer security schemes.

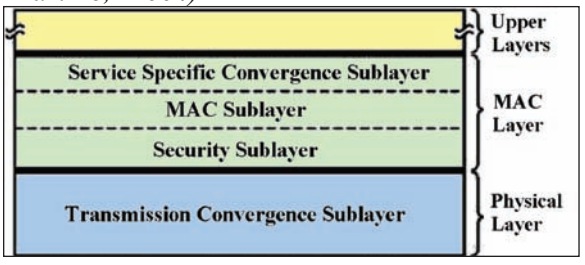
MAC Layer Security

IEEE 802.16 specifications for security mainly fall within the MAC layer. Figure 1 shows the protocol layering of 802.16 and the MAC layer's security implementation. The separate security sublayer provides authentication, secure key exchange, and encryption.

Security within the MAC layer is called the *security sublayer*. Its goal is to provide access control and confidentiality of the data link.

When two parties establish a link, they are protected via a set of protocols that ensure confidentiality and unique access of the authorized parties. The unique handshaking between the two

Figure 1. IEEE 802.16 lower layers (Adapted from "Part 16," 2004)



entities; namely BS and subscriber station (SS), is done at the MAC layer through security sublayer, which has five entities (Chandra, 2002):

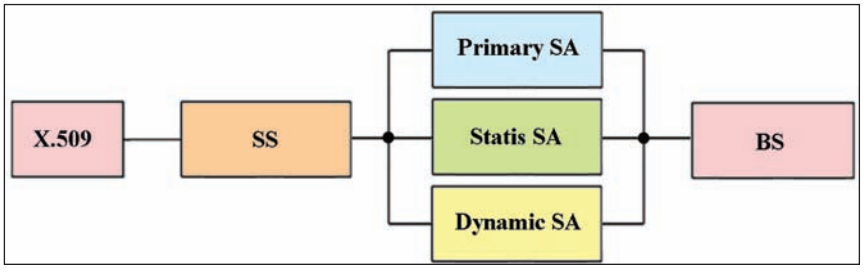
- **Security associations:** A security association (SA) is a set of security information parameters that a BS and one or more of its client SSs share in order to support secure communications. Three types of SAs are defined as (Johnston & Walker, 2004) *primary*, *static*, and *dynamic* (Figure 2), which define the security keys and associations established between a SS and a BS during the authorization phase.
- **X.509 certificate profile:** This defines a digital certificate to verify the identity of subscribers and prevents impersonation (unauthorized SS or BS)
- **PKM authorization:** The privacy key management (PKM) protocol is responsible for privacy, key management, and authorizing an SS to the BS. The initial draft for WiMAX mandates the use of PKMv1 (Johnston & Walker, 2004), which is a one-way authentication method. PKMv1 requires only the SS to authenticate itself to the BS, which poses a risk for a MITM attack. To overcome this issue, PKMv2 was proposed (later adopted by 802.16e), which uses a mutual (two-way) authentication protocol. Here, both the SS and the BS are required to authorize and authenticate each other
- **Privacy and key management:** The privacy of the communications between the SS and the BS is achieved through the PKM protocol. Phifer, L 2. (2003, September). Applying RADIUS to Wireless LANs, using RADIUS For WLAN Authentication, Part I, from http://www.wi-fiplanet.com/tutorials/article.php/10724_3114511_1
- **Encryption:** The data communication between each SS and BS is encrypted using the advanced encryption standard (AES), with at least 128 bit keys. According to FIPS 140-2, AES-128 is computationally secure for data up to SECRET level for the next 10 years.

According to the initial drafts of WiMAX, the security sublayer provides enough security mechanisms to provide privacy, authentication, and encryption over the airlink. However, in order to achieve maximal security strength, true end-to-end security is required for a corporate wireless backbone, which enhances the security mechanisms specified by the initial drafts.

Security at Upper Layers

IEEE 802.16's main focus on the security issue is at the MAC layer, therefore WiMAX has the

Figure 2. Security model of the privacy sublayer (Adapted from Barbeau, 2005)



freedom to adopt the strong security measures for upper layers (network, transport, session, and application layers). Upper layer security options, such as Internet protocol (IP) security protocol (IPSec) and transport layer security (TLS), are examples of the current security schemes for upper layers. Through this freedom of choice, the security strength of WiMAX is comparable to the most secure networks in the market.

Lawful Interception (LI) or Lawful Legal Interception (LLI) (Baker, Foster, & Sharp, 2004; Brown, 2006; Mulholland, 2006)

Since WiMAX-enabled nodes will be connected as parts of the worldwide telecommunications networks and the telecommunications infrastructure of the world, the need for law enforcement access is required. Standards for access to the IP-based networks such as WiMAX have already been developed and are available from various standards and government bodies worldwide.

What follows is a discussion that focuses on two major standards bodies, the ETSI (European Telecommunications Standards Institute) and the IETF (Internet Engineering Task Force).

ETSI Approach to Lawful Interception

The Technical Committee on Lawful Interception (TCLI) is the leading body for lawful interception standardization within ETSI. Lawful interception standards have also been developed by ETSI technical bodies: AT, TISPAN (SPAN and TIPHON™), TETRA, and by 3GPP™. European governments might expect WiMAX vendors to provide this law enforcement access. Examples of ETSI standards include: "

- *ES 201 671: Lawful Interception (LI); Telecommunications Security; Handover Interface for the Lawful Interception of Telecommunications Traffic (revised version).*
- *ES 201 158: Lawful Interception (LI); Telecommunications Security; Requirements for Network Functions*
- *TS 102 234: Lawful Interception (LI); Telecommunications Security; Service-specific details for internet access services.*
- *TS 102 233: Lawful interception (LI); Telecommunications Security; Service-specific details for e-mail services.*
- *TS 102 232: Lawful Interception (LI); Telecommunications Security; Handover Specification for IP Delivery.*
- *TS 101 671: Lawful Interception (LI); Telecommunications Security; Handover interface for the lawful interception of telecommunications traffic.*
- *TS 101 331: Lawful Interception (LI); Telecommunications Security; Requirements of Law Enforcement Agencies.*
- *TR 102 053: Lawful Interception (LI); Telecommunications Security; Notes on ISDN lawful interception functionality.*
- *TR 101 944: Lawful Interception (LI); Telecommunications Security; Issues on IP Interception.*
- *TR 101 943: Lawful Interception (LI); Telecommunications Security; Concepts of Interception in a Generic Network Architecture.*" (copied from Arend, 2007).

IETF Decision on the Lawful Interception

The IEFT has yet to consider wiretap requirements as part of their standards. The reasons for this decision are:

- Inappropriate in global standards – legal and privacy requirements are too varied
- Would increase protocol complexity and decrease security
- End-to-end security makes LI unworkable
- Other standards are already available

The IETF believes that designed mechanisms, which facilitate or enable wiretapping, or methods of using other facilities for such purposes, should be described openly, so as to ensure the maximum review of the mechanisms and to ensure that they adhere as closely as possible to their design constraints. This is considered by Cisco (Figure 3) for

LI in IP networks (RFC 3924) with the following requirements (Mulholland, 2006).

Carriers should be able to provide the following:

- **Content of the communication**
  - Audio content of the voice call
  - Packets to and from the subject
- **Communication-identifying information (CmII)**
  - Dialed digits in voice calls
  - Subject login information
  - Network addresses data

LI should not be detectable by the intercept subject and should include the followings:

- Knowledge of wire-tapping is limited to authorized personnel.
- Ability to correlate communication identifying information with the content of the communication.
- Confidentiality, authentication, and integrity of the CmII.
- Requirements vary between different agencies, regions, and countries.

Lawful access (LA) requirements are:

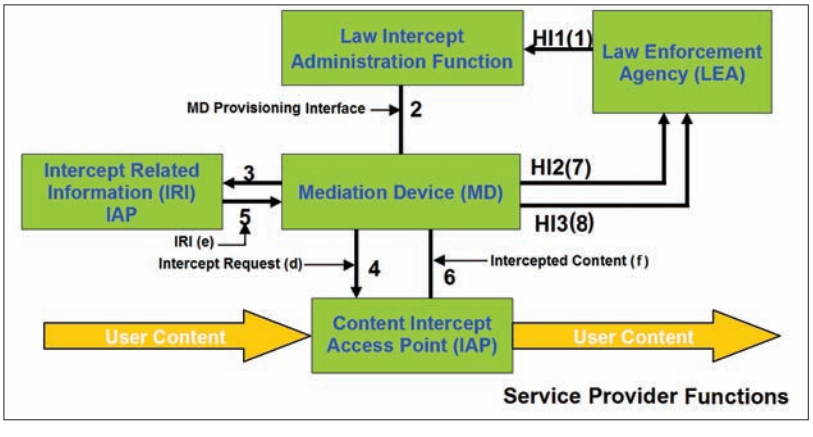
- Invisible to unauthorized personnel and other interceptors.
- Undetectable to the subject.
- Any available decryption keys should be provided to the authorities.
- Only authorized information should be provided.

SECURITY OF IMS AND WIMAX

The IP multimedia subsystem (IMS) uses a standardized next generation networking (NGN) architecture for wireline as well as wireless systems. This is particularly important for WiMAX backbones as they offer the required bandwidth for such multimedia traffic. More importantly is the fact that WiMAX comes in several flavors, some of which may coexist in a single network: fixed, portable, nomadic, and mobile. Therefore WiMAX covers wide areas of broadband access for personal and cellular communications, inline with the IMS coverage.

IMS provides new services as well as current and future Internet related services. This includes end-users ability to execute all related commands and functions even when they are far from their home networks, roaming through foreign networks. In order for IMS to achieve these goals, the architecture of IMS uses the open standard IP protocols, which is defined by the IETF and is enhanced by the 3rd Generation Partnership Project (3GPP). There are three variations of how

Figure 3. Lawful intercept architecture reference model (Adapted from Mulholland, 2006)



IMS works: session initiations between two IMS users, between an IMS user and a user on the Internet, or between two users on the Internet. IMS uses similar protocols for such initiations. Furthermore, service developers use IP protocol stack for the interfaces, which is why IMS can truly merge the Internet with the cellular world. This merge is done by using the cellular and mobile technologies, which provide ubiquitous access and Internet connections, which provides appealing services. Accordingly, WiMAX enjoys one of the most enhanced cellular technologies, which could work in the most efficient method delivering IMS data and applications.

In regards to the IMS security requirements, WiMAX security mechanisms are there to ensure all communicating parties, which gain access to the media, are legitimate and all parties wishing to gain access are thoroughly authenticated through the authentication and authorization protocols. This has to be done before any access is permitted. An ongoing mutual authentication mechanism ensures no illegitimate entity can highjack a session and abduct an already authenticated link and take over the communications at any points.

IMS is designed to work on either fixed or mobile systems. Since WiMAX offers most of the advantages of fixed networks, it is expected that IMS is going to be offered on a pure WiMAX backbone to address corporate and end-user requirements. The fact that WiMAX is based on an all-IP core structure makes it a perfect match for IMS, with its so many IP-based services in use. These services include voice over IP (VoIP), push to talk over cellular (POC), multiparty games, videoconferencing, messaging, community services, presence information, and content sharing.

Security of VoIP

One of the most important applications of IMS is the VoIP that runs over the standard IP. A VoIP system uses protocols, such as, H.323, MGCP, MEGACO, and/or session initiation protocol (SIP) for signaling, and real time protocol/real time control protocol (RTP/RTCP) for media transport and control. The threats for this type of scenario (client/server), as well as in IMS/WiMAX applications, including (Ramana Mylavarapu, 2005):

- Client impersonation (unauthorized client seeks access)
- Server impersonation (unauthorized server pretend to be authorized)
- Message tampering (additions, deletions, or delay of the message contents)
- Session tampering/hijacking (once the session between a legitimate client and server is established, an unauthorized entity takes the session)
- Signaling requests resulting in DoS attacks

To protect against any of the aforementioned vulnerabilities, an extensive two-way authentication method is used to ensure both the client's and the server's right of access and the establishment of IPSec security associate with the IMS terminal. This prevents the mentioned vulnerabilities as well as snooping attacks and replay attacks and to protect the privacy of every individual user.

Security issues in regards to SIP could also be summarized as follow (Access security for IP-based services, 2002):

- Protection mechanism of SIP signaling between the IMS server and the subscriber
- Subscriber's self authentication mechanism
- Subscriber's authentication mechanism to the IMS server

The reactive and proactive security measures are the encryption/decryption of SIP messages and deploying interconnection border control function (IBCF). IBCF is used as a gateway to external networks and provides network address translation (NAT) and firewall functions (Mylavarapu, 2005), two-way authentication-authorization schemes, and secure tunneling.

To enhance the deployment of IPSec, it is recommended to deploy IPv6 (Saito, 2003), which is the next generation Internet protocol. The important factor of IPv6 is its mandate for utilizing IPSec. Using a two-way IPSec connection (two one-way IPSec patterns) is required for an end-to-end security scheme (Saito, 2003).

END-TO-END APPROACH IN WIMAX

As mentioned earlier, the E2E scheme will ensure that the entire link from the user to the server is protected. E2E security is a major issue that could be addressed either in a peer-to-peer basis or in a multilayer manner. The E2E approach discussed here will not offer a comprehensive solution to the multilayer E2E; rather, it will present a peer-to-peer approach (i.e., BS to SS).

The heart of the airlink security scheme in WiMAX is the privacy key management version 2 (PKMv2), which offers a mutual authentication method to authenticate both the SS and the BS.

The following attacks could be mounted if the PKMv2 is not deployed:

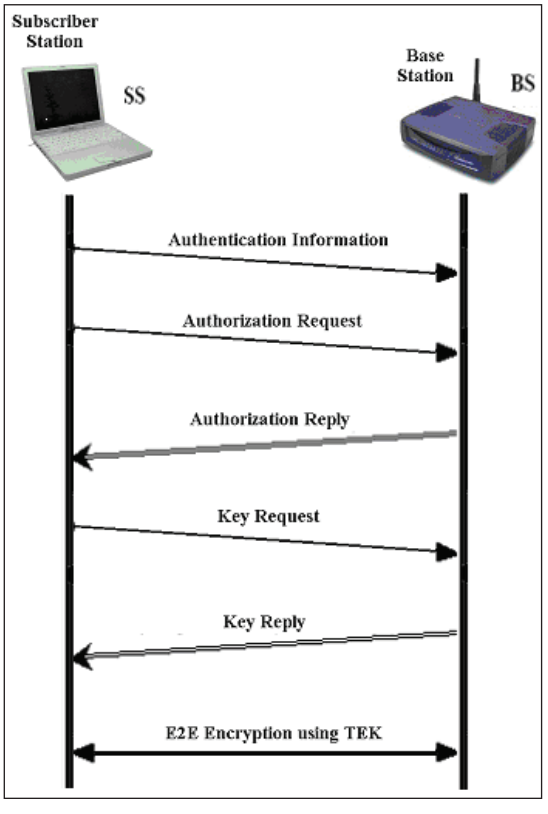
- **BS and SS impersonations:** BS and SS should be able to authenticate the other party and find the unauthorized entity. The use of mutual authentication through PKMv2 (Figure 4) with suitable credentials. PKMv2 supports two authentication protocol schemes: Rivest-Shamir-Adleman (RSA) and extensible authentication protocol (EAP). EAP is mandatory for all devices.
- **Man-in-the-middle-attack:** This type of attack happens when one of the communication parties is not forced to authenticate itself. The same as the BS-SS impersonation. The use of PKMv2 will solve this problem.
- **Key exchange issue:** To encrypt and decrypt information between two parties, temporal keys and sessions keys are used. The key distribution in the initial draft uses triple data encryption standard (3DES) for exchanging keys. A 2-key 3DES based-key wrap is currently used for temporal encryption key (TEK) exchange. TEKs should not be used more than one time and there should be a mechanism to ensure that TEKs do not repeat. Otherwise this suffers from replay attacks as there are no dynamic components in the key exchange protocol and it also suffers from the man-in-the-middle attacks. To avoid this problem, various TEKs should be used and the EAP authentication framework and the AES-counter for cipher-block-chaining message authentication code (CCM) cipher suite should be used with PKMv2.

PKMv2 authentication/authorization method is shown in Figure 4.

WIMAX VS. 3G TECHNOLOGIES

In this section, 3G cellular technologies such as global system for mobile communications (GSM), universal mobile telecommunications system (UMTS), and coded division multiple access (CDMA) are compared with Mobile-WiMAX (802.16e), as they all fall into the cellular technology category. Mobile-WiMAX is a good alternative to the current 3G technologies.

Figure 4. The 2-way authentication and authorization of PKMv2 (Adapted from Adibi, Bin, Ho, Agnew, & Erfani, 2006)



Security Breaches in 3G Technologies

GSM has been around for quite some time and the security mandates in GSM were designed according to the security requirements of when it was designed. Therefore GSM networks suffered several security issues (i.e., one-sided authentication mechanisms). As the technology evolved and matured, GSM/UMTS and CDMA provided the market with stronger security options.

Here are short descriptions of the security problems associated with 3G technologies:

- **Subscriber identity module (SIM) forgery:** SIM cards, mostly used in GSM and GPRS systems, are subject to security threat of forgery due to one-way authorization techniques.
- **Wireless application protocol (WAP) is insecure:** GSM uses WAP for data security, which is considered insecure.
- **Communication signaling in the clear:** Most GSM communication signaling is in the clear with no protection or encryption. This makes it prone to a variety of attacks.
- **Insecurity of base station:** GSM base stations are prone to man-in-the-middle attack scenarios, due to the one-way nature of the authentication scheme.
- **Encryption disability:** UMTS systems are susceptible to a downgrade attack, which eliminates the encryption. An attacker could disable the encryption and trap a legitimate user in a false base station scenario.
- **International mobile subscriber identity (IMSI) security issue:** For first-time registration of users, the IMSI is sent in clear text and an illegitimate entity could take over the session
- **Authentication key agreement (AKA) issue:** Both UMTS and CDMA use AKA. AKA is based on a challenge protocol, which is an unbalanced technique and AKA relies on the availability of a tamper-resistant smart-card in the device, which is also considered to be breakable
- **Cellular authentication and voice encryption (CAVE) issue:** CDMA uses CAVE, which is based on 64-bit authentication key (A-key) and an electronic serial number (ESN). CAVE and ESN are consider computationally weak when a brute force attack is launched against them

Mobile-WiMAX (802.16e)

The WiMAX specification mandates AES-CCM (Barbeau, 2005) encryption (equivalent to FIPS 140-2) between customer premises equipments (CPEs) and the base stations, protecting both the MAC and the PHY layers. The device key management is based on X.509 digital certificates public key, which uses RSA as the public encryption algorithm and other security measures (i.e. confidentiality) are based on AES.

A true E2E security scheme, which is very hard to achieve in 3G technologies, is also available in 802.16e through the use of PKMv2. Therefore Mobile-WiMAX outperforms the strongest members of the 3G family.

CONCLUSION

WiMAX has both a sophisticated set of security protocols in its security suite and advanced bandwidth allocation mechanisms, which makes it a suitable candidate for enterprise applications. The E2E security scheme is capable of providing maximum security for all data and control signals between SSs and BSs. This chapter was intended to take a closer look at the E2E security scheme for WiMAX and to address corporate security requirements. These requirements, which could be addressed by WiMAX, are as follows.

Multi-Level Security and Control ("Product Overview," 2006)

Corporate servers are usually located in highly secured data centers. All data frames should be protected with 128-bit AES encryption technique on an end-to-end basis. Multiple levels of password and authentication methods can be used. These re-

quirements are supported by the security mandates of WiMAX, specified by the current standards.

End-user Remote-Access
End-users are able to connect remotely to a far-away server location using a secure wireless tunnel and access multimedia data and transmit private information. Remote-access is the basic requirement of a VPN and through the deployment of WiMAX, a secure and efficient VPN is achievable.

End-User Security Through Encryption (Data Security)
- AES with 128-bit keys protects the data stream automatically.
- Authentication using dual passwords and end-to-end user authentication.
- BS and CPE Security: BS, CPE, and other devices could be protected through ad-on security features.

Device Authentication
- Devices connected to the backbone of an enterprise will be authenticated, authorization, and protected using authentication, authorization, and certification techniques (i.e., PKMv2, X.509, etc.).
- There should be a complete logging of authorized and unauthorized devices. This will allow tracking of any security violations.

Secure IMs For Fixed And Mobile Applications
Using both fixed- and mobile-WiMAX on the backbone of an enterprise or a corporate server, users will have access to the variety of IMS applications and data, including secure VoIP applications and other VPN access techniques.

Security at the CPE
The security implementations at the customer premises equipments are required to be very high as they are the gateways between the subscriber stations and the services provider.

WIMAX vs. WI-FI
Fixed- and especially mobile-WiMAX outperform the security strength in the latest version of the 802.11 family (802.11i), though 802.16e and 802.11i have many features in common.

WIMAX and IMs Security
The security features in WiMAX are mostly applied at the MAC layer (layer II), where the security sublayer is located. However, WiMAX has the option to adopt very strong security features implemented at the higher layers (i.e., application layer) to meet minimum security requirements for IMS applications.

Security in Fixed- and Mobile- WIMAX
Even though security options built into the mobile-WiMAX are stronger, due to the physical variations and conditions, there has been enough security built into both fixed and mobile WiMAX to ensure complete security from the end-user and VPN applications.

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Chapter XLVIII
Evaluation of Security Architectures for Mobile Broadband Access

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ABSTRACT

During the last few years, mobile broadband access has been a popular concept in the context of fourth generation (4G) cellular systems. After the wide acceptance and deployment of the wired broadband connections, such as DSL, the research community in conjunction with the industry have tried to develop and deploy viable mobile architectures for broadband connectivity. The dominant architectures which have already been proposed are Wi-Fi, universal mobile telecommunications system (UMTS), WiMax, and flash-orthogonal frequency division modulation (OFDM). In this chapter, we analyze these protocols with respect to their security mechanisms. First, a detailed description of the authentication, confidentiality, and integrity mechanisms is provided in order to highlight the major security gaps and threats. Subsequently, each threat is evaluated based on three factors: likelihood, impact, and risk. The technologies are then compared taking their security evaluation into account. Flash-OFDM is not included in this comparison since its security specifications have not been released in public. Finally, future trends of mobile broadband access, such as the evolution of WiMax, mobile broadband wireless access (MBWA), and 4G are discussed.

INTRODUCTION

During the last decade, wireless network technologies have greatly evolved and have been able to provide cost-efficient solutions for voice and data services. Their main advantages over wired networks are that they avoid expensive cabling infrastructure and they support user mobility and effective broadcasting. As a result, mobile wireless networks have managed to take over a large percentage of the "voice" market, since the global system for mobile communications (GSM) cellular technology has promoted the worldwide expansion of mobile telephony. Furthermore, nowadays broadband Internet has become a necessity for many home and business users. Moreover, in the context of all-IP network convergence, an increasing share of telephony subscribers is migrating towards VoIP solutions mainly due to the decreased cost compared to fixed telephony. Therefore, the main challenge is to find spectrum- and cost-efficient solutions for the provision of mobile broadband services. In this direction, a large research community of academic and industrial origin has dedicated considerable effort on designing, implementing, and deploying systems for mobile broadband access, such as Wi-Fi, universal mobile telecommunications system (UMTS), WiMax, and flash-orthogonal frequency division modulation (OFDM). According to the predictions, in the years to come, more and more of our voice samples and data packets will be carried over wireless broadband links through the Internet. Therefore it becomes imperative that these messages are secured from malicious eavesdroppers and attackers. Especially in applications such as e-banking, e-commerce, and e-government the revelation of sensitive data to unauthorized persons, unauthorized data submission, and/or the interruption of system availability can cause financial damage, user preferences' surveillance, industry espionage, and/or administrative overhead.

The purpose of this chapter is to analyze and compare the security architectures of the dominant mobile broadband technologies. More specifically, the objectives are to:

- Describe and analyze the security architectures of mobile broadband technologies.
- Identify the strong and weak points of each technology in terms of access control based on authentication, confidentiality, integrity, and physical layer resilience.
- Compare the investigated security architectures based on a risk evaluation of the identified security vulnerabilities.

MOBILE BROADBAND TECHNOLOGIES

This section discusses the mobile technologies Wi-Fi, UMTS, WiMax, and flash-OFDM. Authentication performance, confidentiality, and integrity mechanisms for each technology are analyzed.

Wi-Fi

Wi-Fi was the first widely-deployed technology for wireless computer networks. It was originally designed to provide portability support in local area networks (LANs). However, Wi-Fi has also been utilized in other scenarios, such as wireless metropolitan area networks (WMANs), since it was the first wireless technology with support for mobile communication and for a wide range of portable and mobile devices.

The Wi-Fi radio interface is based on the IEEE 802.11 standard and is available in three versions:

- **802.11a**
  - **Frequency:** 5.5 GHz,
  - **Modulation:** OFDM
  - **Bandwidth:** 54 Mbps
- **802.11b**
  - **Frequency:** 2.4 GHz
  - **Modulation:** Direct sequence spread spectrum (DSSS)
  - **Bandwidth:** 11 Mbps
- **802.11g**
  - **Frequency:** 2.4 GHz
  - **Modulation:** OFDM
  - **Bandwidth:** 54 Mbps

In this context, Wi-Fi alliance is an organization testing products in order to evaluate that they correctly implement the set of standards defined in the IEEE 802.11 specification. After the products have successfully passed these tests, they are allowed to use the Wi-Fi logo.

Security Architecture

Wi-Fi security standards include wired equivalent privacy (WEP), Wi-Fi protected access (WPA), and WPA2. WEP was the first introduced security standard. WPA was designed to be a security protocol that corrects the security deficiencies of WEP and to be backward compatible with existing hardware. The last development in Wi-Fi security is the WPA2 standard which was published in June 2004 by the IEEE 802.11i group. WPA2 was designed to offer a further improved security scheme (Edney & Arbaugh, 2003). The aforementioned security specifications are analyzed and compared in the following paragraphs.

Authentication

Authentication services are utilized to allow a client to communicate with the serving access point. After successful authentication, a session is initiated and it can be terminated by either the client or the access point. Wi-Fi provides the following link-layer authentication schemes:

- Closed system authentication
- Media access control (MAC) filtering
- WEP suthentication—Shared RC4 key
- WPA and WPA2 authentication—802.1X/extensible authentication protocol (EAP)

Closed system authentication, MAC filtering, and WEP authentication are not recommended due to their well-known serious security flaws (Borisov, Goldberg, & Wagner, 2001; Lynn & Baird, 2002; Welch & Lathrop, 2003).

WPA and WPA2 security schemes have some major design differences from WEP, since the authentication and the confidentiality processes operate totally independently from each other (Baek, Smith, & Kotz, 2004). The authentication process of WPA and WPA2 adopts the three-entity model of IEEE 802.1x which was originally designed for the point-to-point protocol (IEEE, 2001). The three entities involved in this protocol are the client, the access point (AP), and the authentication server (AS). First, the client request to obtain access to the network. The AP acts as a network guard, allowing access only to the clients that the AS has authenticated. Finally, the AS is responsible for deciding whether the client is allowed to access the network. These three entities utilize EAP to exchange communication messages in order to coordinate the authentication process (Stanley, Walker, & Aboba, 2005).

In addition, there is a lighter version of WPA, called WPA-preshared key (WPA-PSK). This version is based on a shared secret key or passphrase in order to authenticate the wireless clients. As a result, an attacker can use a wireless sniffer to capture the 4-way WPA handshake, log the packets, and then try a brute force attack using a dictionary file (Van de Wiele, 2005). Thus, if WPA-PSK is deployed, the robustness of the network security totally depends on the length and the complexity of the secret key.

Encryption

Encryption services are utilized to provide confidentiality over wireless communication links. In Wi-Fi networks the following encryption schemes are available:

- WEP based on the RC4 (Ron's Code 4) stream cipher
- WPA encryption based on the temporal key integrity protocol (TKIP)
- WPA2 encryption based on the advanced encryption standard (AES)

WEP is a weak implementation of the RC4 stream cipher and WEP encryption is thus not recommended (Borisov et al., 2001; Stubblefield, Ioannidis, & Rubin, 2002; Welch & Lathrop, 2003).

WPA encryption is based on TKIP. It incorporates the basic functionalities of WEP, but improvements have been made to address the security flaws. The length of the initialization vector (IV) has been increased from 24 bits to 48 bits and therefore the possibility of reused keys has been significantly decreased. Furthermore, WPA does not directly utilize the master keys. Instead it constructs a hierarchy of derived keys to be utilized in the encryption process. Finally, WPA dynamically cycles keys while transferring data. Since keys are regularly changed, a malicious user has a very short time window to attempt an attack.

WPA2 was designed from scratch taking the vulnerabilities of the previous security architectures into account. WPA2 allows various network implementations, but the default configuration utilizes the advanced encryption standard (AES) and the counter mode CBC MAC protocol (CCMP). AES is a block cipher, operating on blocks of 128 bit data, and is a replacement of the RC4 algorithm used by WPA. AES is much more robust since it has already been tested in various security architectures without revealing serious vulnerabilities. CCMP comprises of two main parts. The first is the counter mode (CM) which is responsible for the privacy of the data in combination with AES. The second is the cipher block chaining message authentication code (CBC-MAC) providing data integrity checking and authentication.

Integrity

Integrity services are responsible for making sure that transmitted information is not replayed or modified during transmission. The following techniques are applicable in Wi-Fi networks:

- WEP cyclic redundancy heck 4 (CRC-32) Checksum
- WPA Integrity
- WPA2 Integrity

WEP checksum is a noncryptographic linear function of the plaintext. This means that multiple messages may correspond to a single 32-bit number. Hence, an experienced intruder could modify the plaintext in such a way that the checksum remains unchanged. Furthermore, due to the linearity of both the RC4 stream cipher and the CRC-32 checksum, the attacker is able to change the message even when he does not know the plaintext (Welch & Lathrop, 2003).

WPA has incorporated mechanisms for the prevention of replay attacks. More specifically, the TKIP sequence counter (TSC) based on the IVs is utilized, so that the receiver can identify and reject "replayed" messages. Furthermore, WPA uses an improved integrity mechanism in order to generate the message integrity check (MIC). This mechanism, called Michael, is able to detect possible attacks and deploy countermeasures to prevent new attacks.

WPA2 utilizes CCMP for providing integrity services. CCMP generates a MIC using the CBC-MAC method. In this method, even the slightest change in the plaintext will produce a totally different checksum.

Security Vulnerabilities

Although the Wi-Fi security architecture has been greatly improved since WEP, there are still vulnerabilities which cannot be addressed by WPA2. These vulnerabilities can lead to a number of link layer denial-of-service (DoS) attacks (Van de Wiele, 2005). All the DoS techniques described here are fairly easy to use with freely available tools found on the Internet. In most of the cases, the attacker will use different forged MAC addresses to mount DoS attacks. These attacks can be detected by specialized hardware (e.g., air monitor, security aware access point) which can detect the misuse of the infrastructure. Furthermore, this specialized hardware can notify the people responsible for the follow-up of a DoS incident and give an estimate on where the attacker is located by considering the signal and noise levels.

Disassociation Storm

Before any wireless communication can occur, a client has to send an association frame to the access point asking to join the network. Similarly,

after the end of the wireless session, the access point or client has to send a disassociation frame to terminate the connection. The frames of these messages are broadcasted and can be sniffed by an attacker. The attacker can then flood the network with spoofed disassociation frames every time the client tries to join the network, thus disrupting the association process and the network access.

Authenticated / Deauthenticated Storm

The aforementioned principle can be exploited in order to disconnect a client and try to keep the client disconnected. This technique starts by sending a spoofed deauthentication frame followed by a disassociation frame in order to make sure that the client has disconnected from the legitimate access point. In a more advanced version of this attack, a fake probe request and some beacon frames are transmitted in order to force the client to connect to a rogue access point which ignores or monitors the client's traffic.

UMTS

Universal mobile telecommunications system (UMTS) is one of the third generation (3G) wireless cellular technologies for mobile communication. Mobile devices like smartphones, laptops, and handheld computers can be used. UMTS is standardized by the 3G partnership project (3GPP) and it is mainly deployed in Europe and Japan. Theoretically UMTS supports up to 1920 Kbps data transfer rates, but currently the real world performance can reach 384 Kbps. It uses the W-code division multiple access (CDMA) technology over two 5 MHz channels, one for uplink and one for downlink. The specific frequency bands originally defined by the UMTS standard are 1885-2025 MHz for uplink and 2110-2200 MHz for downlink.

In UMTS network topology, a mobile station is connected to a visited network by means of a radio link to a particular base station (Node B). Multiple base stations of the network are connected to a radio network controller (RNC) and multiple RNCs are controlled by a general packet radio service (GPRS) support node (GSN) in the packet-switched case. The visitor location register (VLR) and the serving GSN keep track of all mobile stations that are currently connected to the network. Every subscriber can be identified by its international mobile subscriber identity (IMSI). In order to protect against profiling attacks, this permanent identifier is sent over the air interface as infrequently as possible. What is more, locally valid temporary mobile subscriber identities (TMSI) are used to identify subscribers whenever possible. Every UMTS subscriber has a dedicated home network with which the subscriber shares a long term secret key Ki. The home location register (HLR) keeps track of the current location of all subscribers of the home network. Mutual authentication between a mobile station and a visited network is carried out with the support of the current serving GSN (SGSN) or the mobile switching center (MSC)/VLR respectively.

The new series of 3.5G mobile telephony technologies, known as high speed packet access (HSPA), will provide more bandwidth to the end-user, improved network capacity to the operator, and enhanced interactivity for data applications. HSPA refers to the improvements made in the UMTS downlink, known as high speed downlink packet access (HSDPA), and the UMTS uplink, usually referred to as high speed uplink packet access (HSUPA) but also referred to as enhanced dedicated channel (E-DCH).

HSDPA provides a bandwidth of 14.4 Mbps/user. For multiple-input-multiple-output (MIMO) systems up to 20 Mbps can be achieved. Both HSDPA and HSUPA can be implemented in the standard 5 MHz carrier of UMTS networks and can coexist with original UMTS networks. As HSPA specifications refer only to the access network, there is no change required in the core network (CN) except from the high data-rate links required to handle the increase in clients' traffic generated by HSPA.

Security Architecture

The 3G security architecture is based on GSM, but certain improvements are added in order to correct the described security vulnerabilities.

Authentication

Authentication and key agreement (AKA) is the main security protocol of UMTS in the 3GPP specification. According to AKA, a mobile device and a base station have to authenticate each other. Figure 1 provides an overview of the AKA process. The authentication vector includes the following components:

a. A random number (RAND)
b. An expected response (XRES)
c. A cipher key (CK)
d. An integrity key (IK)
e. An authentication token (AUTN)

RAND and XRES are utilized by the network to authenticate the mobile station (MS), whereas AUTN is utilized by the MS to authenticate the network. After the mutual authentication, the two communicating parties can agree on the CK and the IK which will be used throughout the rest of the session.

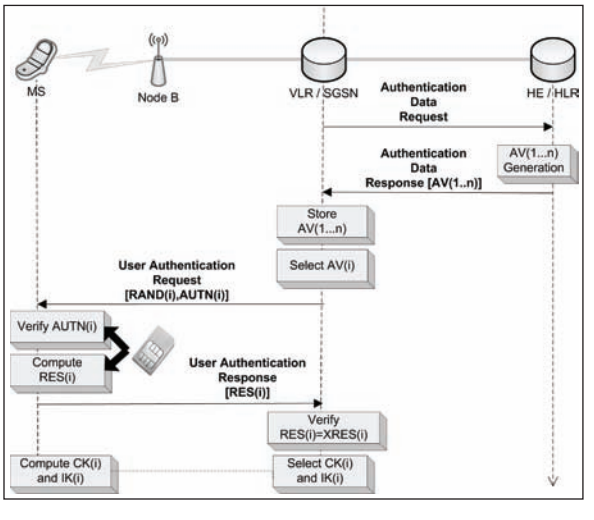
Confidentiality and Integrity

UMTS employs the UMTS encryption algorithm (UEA) in order to provide information confidentiality. The encryption process of UEA is based on the f8 algorithm. One of the main improvements of UMTS is that the link layer encrypted channel is established between the MS and the GSN instead of the BS, as in GSM. Furthermore, UEA is utilized to protect not only the data channels but also certain signalling channels.

For user confidentiality UMTS utilizes the same mechanism as GSM. Instead of the IMSI, a temporary identity (TMSI) assigned by VLR is used to identify the subscriber in the communication messages exchanged with the BS. However, the IMSI is still transmitted in clear-text over the air while establishing the TMSI. This has been proved to be a starting point for security attacks against UMTS.

Data integrity in 3GPP is assured explicitly through the UMTS integrity algorithm (UIA). The UIA operation is based on the f9 algorithm. UIA is utilized to protect both communication and signalling. UEA and UIA are presented in Figure 2.

Figure 1. 3GPP authentication and key agreement (AKA)



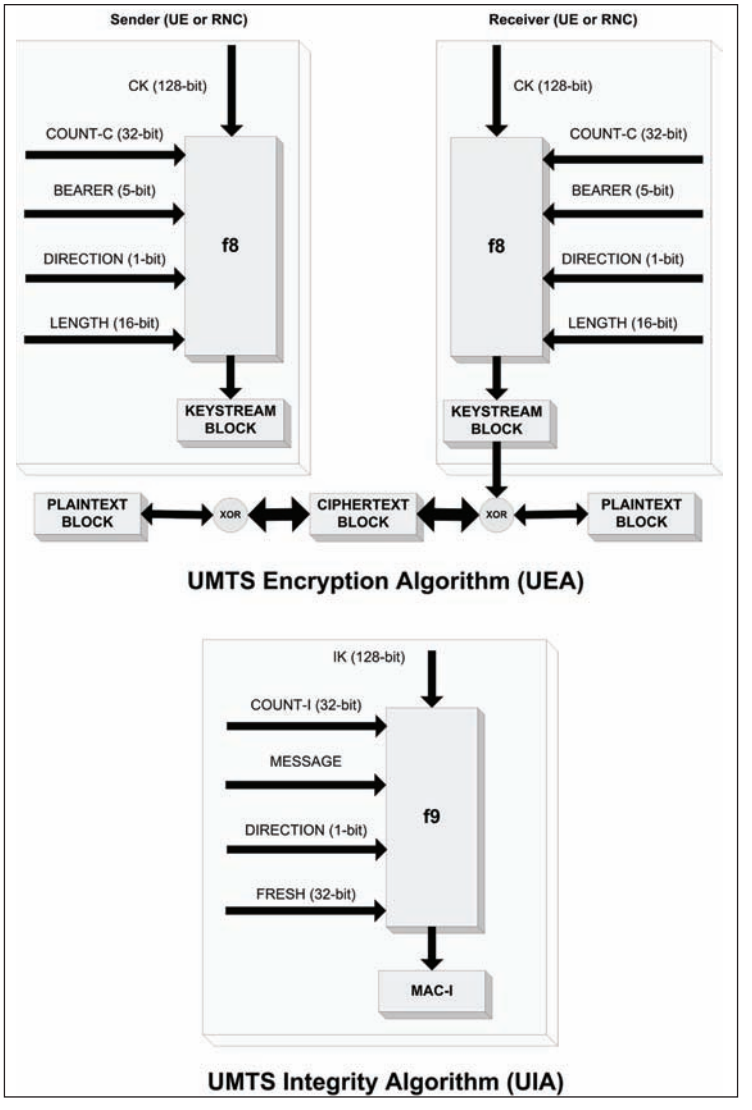
GSM Compatibility

UMTS has been designed to be backwards compatible with GSM. It includes standardized security features in order to ensure world-wide interoperability and roaming. More specifically, GSM user parameters are derived from UMTS parameters using a set of predefined conversion functions. However, GSM subscribers roaming in 3GPP networks are supported by the GSM security context, which is vulnerable to the aforementioned GSM vulnerabilities.

Security Vulnerabilities

3G security has been significantly improved compared to GSM. However, there are still vulnerabilities related to the backwards compatibility with GSM. Meyer and Wetzel (2004a, 2004b) present a man-in-the-middle attack which can be mounted even if the subscriber utilizes a 3G enabled device within a 3G base station coverage. The described attack goes far beyond the anticipations of the 3GPP group. UMTS subscribers are vulnerable

Figure 2. UMTS encryption and integrity algorithm



to what 3GPP calls a "false base station attack" even if subscribers are roaming in a pure UMTS network and even though UMTS authentication is applied.

This attack can be categorized as a "roll-back attack." This category of attacks exploits weaknesses of old versions of algorithms and protocols by means of the mechanisms defined to ensure backward compatibility of newer and stronger versions. According to this technique, the attacker acts on behalf of the victim's mobile station in order to obtain a valid authentication token AUTN from any real network. It is assumed that the attacker has already retrieved the IMSI of the targeted subscriber, since the latter is sent in clear-text when establishing a TMSI. The attacker can capture the AUTN by initiating the AKA procedure with any legitimate network. The next step is to impersonate a valid GSM base station to the victim mobile station. The mobile station connects and verifies the rogue BS, since it possesses a valid AUTN. Subsequently, the rogue BS is configured

by the attacker to utilize "no encryption" or weak encryption. Finally, the attacker can send to the mobile station the GSM cipher mode command including the chosen encryption algorithm. The man-in-the-middle attack is mounted and the attacker can use passive or active eavesdropping without being detected.

WIMAX

The IEEE 802.16 or broadband wireless access (BWA) Working Group was established in 1999 to prepare specifications for broadband wireless metropolitan area networks. The first 802.16 standard was approved in December 2001 and was followed by three amendments: 802.16a, 802.16b and 802.16c. In 2004 the 802.16-2004 standard (IEEE-SA, 2006) was released and the earlier 802.16 documents including the a/b/c amendments were withdrawn. An amendment to the standard 802.16e (IEEE-SA, 2006) addressing mobility was introduced in 2005. The main additions of the 802.16e were low density parity check (LDPC) codes at the physical layer, enhanced MIMO setup functions, new states for MS operation, parameter-defined power saving classes of mobiles, and enhanced FFT sizes for scalable OFDMA.

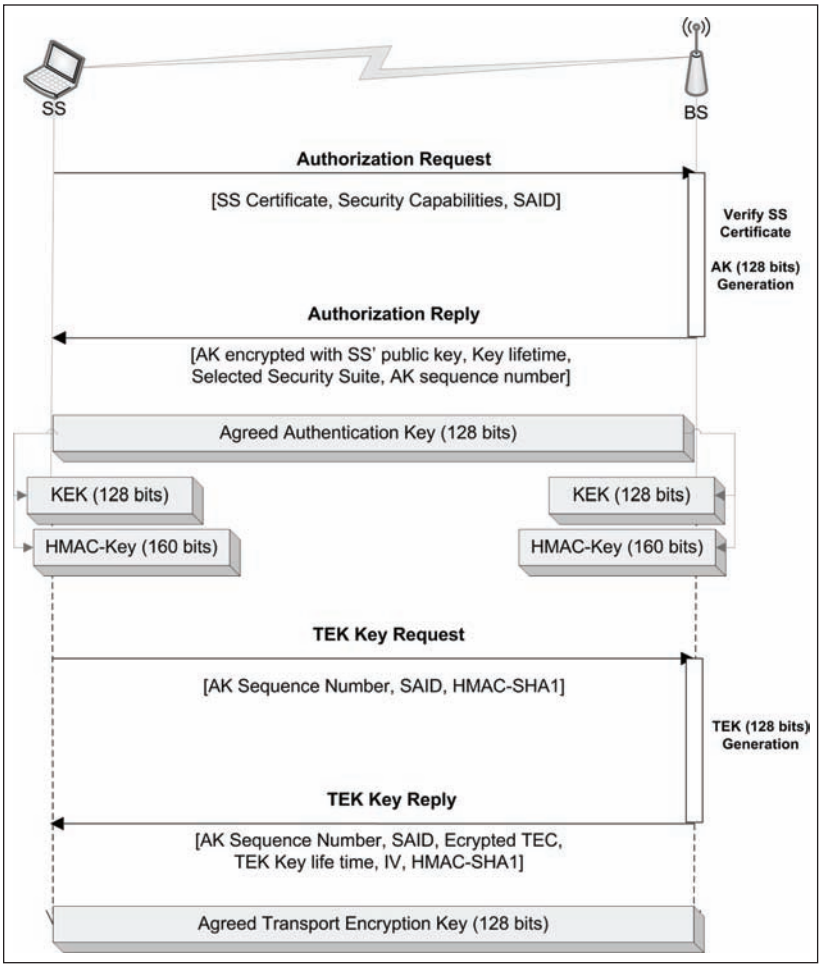
WiMax aims at providing high data rate triple-play wireless services to fixed users, to nomadic users, and to users of mobile devices. It is based on a low latency quality of service (QoS) architecture in order to provide real-time multimedia services. It operates on the 2-6 GHz (IEEE802.16e) and 10-66 GHz (IEEE802.16-2004) frequency bands and it uses the OFDMA technology for modulation and medium access.

Security Architecture

WiMax has been designed with security in mind, especially after the serious vulnerabilities discovered in the original Wi-Fi security protocol. The IEEE 802.16 specifications include a security sublayer within the MAC layer. The IEEE 802.16 security architecture is based on the following issues:

- **Authentication:** The baseline authentication architecture, by default, employs a public key infrastructure (PKI) based on X.509 certificates. The base station (BS) validates the client's certificate before permitting access to the physical layer (see Figure 3). First, the subscriber station (SS) sends to the BS an authorization request containing the certificate, the available security capabilities, and the security association identifier (SAID). The BS verifies the certificate and generates a 128 bit authentication key (AK). Then, the BS sends to the SS an authorization reply, which contains the AK encrypted with SS's public key, the AK's lifetime, the selected security suite, and an AK sequence number. The SS uses its private key to recover the AK, which can now be utilized as an authentication token in further communication.
- **Key exchange:** The SS and the BS can agree on a transport encryption key (TEK), which will be utilized for data encryption (see Figure 3).
  TEK is randomly generated by the BS. The AK established during authentication is used to derive two additional keys:
  - Message authentication key (HMAC key), which is utilized to provide message integrity and AK confirmation during the key exchange process.
  - Key encryption key (KEK), which is utilized for encrypting the TEK before sending it back to the SS. The modes for encrypting TEK are:
    a. 3DES with a 112 bit KEK
    b. AES with a 128 bit KEK
    c. RSA using SS's public key
- **Data encryption and integrity:** The modes for implementing data privacy are:
  - Data encryption standard (DES) with a 56 bit key and cipher block chaining (CBC), which utilizes the Initialization Vectors obtained during Key Exchange,
  - AES with a 128 bit key and counter mode with cipher block chaining message authentication code protocol, which

Figure 3. WiMax authentication and key exchange process



provides message integrity and replay protection.

Security Vulnerabilities

WiMax supports unilateral device level authentication (Barbeau, 2005), which can be implemented in a similar way as Wi-Fi MAC filtering based on the hardware device address. Therefore, address sniffing and spoofing make a MS masquerade attack possible. In addition, the lack of mutual authentication makes a man-in-the-middle attack from a rogue BS possible. However, a successful man-in-the-middle attack is difficult because of the time division multiple access (TDMA) model in WiMax. The attacker must transmit at the same time as the legitimate BS using a much higher power level in order to "hide" the legitimate signal. Furthermore, WiMax supports mutual authentication at user network level based on the generic extensible authentication protocol (EAP) (Aboba, Blunk, Vollbrecht, Carlson, & Levkowetz, 2004). EAP variants, EAP- transport layer security (TLS) (X.509 certificate based) (Aboba & Simon, 1999) and EAP-subscriber identity module (SIM) (Haverinen & Salowey, 2004), are supported.

In the data privacy domain, the main security threat is the transmission of unencrypted management messages over the wireless link. Eavesdropping of management messages is a critical threat for

users and a major threat to a system. For example, an attacker could use this vulnerability to verify the presence of a victim at its location before perpetrating a crime. Additionally, it might be used by a competitor to map the network. Another major vulnerability is the encryption mode based on DES. The 56 bit DES key is easily broken by brute force with modern computers. Furthermore, the DES encryption mode includes no message integrity or replay protection functionality and is thus vulnerable to active or replay attacks. The secure AES encryption mode should be preferred over DES.

Finally, there is a potential for DoS attacks because authentication operations trigger the execution of long procedures. For example, a DoS attack could flood a MS with a high number of messages to authenticate. Due to low computational resources, the MS will not be able to handle a large amount of invalid messages, rendering the DoS attack successful.

FLASH-OFDM

Fast low-latency access with seamless handoff orthogonal frequency division multiplexing (flash-OFDM) is an OFDM-based proprietary system which specifies the physical layer, as well as higher protocol stack layers. It is an all IP technology and it aims to compete with GSM/3G networks. Already implemented flash-OFDM technology operating in the 450 MHz frequency band can offer a maximum download speed of 5.3 Mbps and an upload speed of 1.8 Mbps.

Design objectives have included design of a high capacity physical layer, a packet-switched air interface, a contention-free and QoS-aware MAC layer, and efficient operations using existing Internet protocols. The air interface is designed and optimized across all protocol stack layers. Fast hopping across all tones in a pseudorandom predetermined pattern is employed. Channel coding and modulation are carried out on a per-segment basis and can be individually optimized for each channel. The ability to send segments of arbitrary size enables the MAC layer to perform efficient packet switching over the air interface. Given segments can be dedicated for use with predefined functionality. Thus there is no need to send overheads, such as message headers. Therefore, network layer traffic experiences small delays and no significant delay jitter.

Security Architecture

The security relies on "defence in depth," that is, virtual private network (VPN) tunnelling and end-to-end encryption are used. Security specifications for flash-OFDM have not been presented in public (Lehtonen, Ahonen, Savola, Uusitalo, Karjalainen, Kuusela et al., 2006).

Security Analysis

A security analysis of the mobile broadband technologies Wi-Fi, UMTS, and WiMax is presented. Inclusion of flash-OFDM in this comparison is not possible because of the unavailability of public security specifications. Threats are analyzed with respect to the likelihood of occurrence, the impact on the network operation, and the global risk they represent. In the following paragraphs, we first describe in detail the evaluation and comparison methodology, and then a group of tables is presented in which the security threats of the investigated technologies are evaluated. Security threats are classified based on four main axes: authentication, confidentiality, integrity, and physical layer resilience. Finally, the security evaluations of the studied technologies are compared and presented in a concise overview table.

Methodology

The evaluation and comparison methodology was based on the method described by Barbeau, (2005) and ETSI (2003). More specifically, three main criteria are considered: likelihood, impact, and risk. "Likelihood" refers to the probability that an attack associated with a specific threat is successfully launched. In this context, two variables are considered:

a. The technical difficulties of mounting the attack in terms of the required software, hardware, and estimated time duration.
b. The attacker's motivation in terms of the level of network access or the severity of the system malfunction that the attack achieves.

Three levels of likelihood are available as described in Table 1. "Impact" refers to the consequences of an attack in terms of user and network security. The two variables of impact are:

a. User impact in terms of the severity of network access degradation.
b. System impact in terms of the severity of network degradation or outage.

Three levels of impact are available as described in Table 1. According to the level of likelihood and impact, numerical values from a predefined range are assigned to each criterion (see Table 1). For a specific threat, the "risk" refers to an overall threat level which is determined by the product of the likelihood value and impact value.

Security threats which result in a high evaluated risk value are critical and additional measures should be taken to protect the network perimeter, whereas threats which have a low risk can be tolerated without employing countermeasures.

In this point, it is worth noting that this quantitative ranking is subjective. However, this is a useful evaluation and comparison methodology which can stimulate a structured discussion based on the evaluation criteria, that is, likelihood, impact, and risk. The comparison axes are authentication, confidentiality, integrity, and physical layer resilience.

Table 1. Evaluation and comparison methodology

		Variables		
Criteria	**Cases**	**Difficulty**	**Motivation**	**Rank**
Likelihood	**Unlikely**	Strong	Low	**1**
	Possible	Solvable	Reasonable	**2**
	Likely	None	High	**3**
		User	**System**	
Impact	**Low**	Annoyance	Very limited outages	**1**
	Medium	Loss of service	Limited outages	**2**
	High	Long time loss of service	Long time outages	**3**

Risk = Likelihood x Impact			
Risk	**Minor**	No need for countermeasures	**1-3**
	Major	Threat need to be handled	**3-6**
	Critical	High priority	**6-9**

Objective-Based Comparison

This section applies the aforementioned methodology on four main objectives of wireless security architectures: authentication, confidentiality, integrity, and physical layer resilience. For each objective, a thorough discussion describes the rationale behind the ranking of the security threats.

Authentication Evaluation

Wi-Fi includes four security threats which are all ranked to have a high impact on the system, since the attacker can exploit them to override the authentication checks or launch a combination of attacks which will grant him full network access. However, the likelihood ranking greatly varies. Closed system authentication and MAC filtering are very likely to be attacked by sniffing software which is readily available on the Internet. WEP attacks are more complicated, because a combination of software is required to induce and capture network traffic and then exploit the weak IVs in order to crack the key. WPA-PSK is even more difficult to break since it requires a brute force attack. The resilience of WPA-PSK is greatly dependent on the length and the complexity of the preshared key.

UMTS is far more resilient to authentication attacks, since most of the security gaps have been identified during the deployment of GSM and tackled in the specification design of UMTS. However, UMTS includes two main authentication vulnerabilities which can be exploited to launch a man-in-the-middle attack (high impact). The IMSI hijack threat refers to the deployment of a rogue BS in order to initiate an authentication procedure and steal the IMSI of a mobile user. The motivation for this attack is high, but the equipment is expensive and complicated to configure. AUTN capture is the second step of the attack and it refers to capturing an authentication token by masquerading a MS.

It assumes that the IMSI Hijack attack has been already successfully launched. However, this attack does not require the deployment of a rogue BS and therefore it is more possible to happen.

In the WiMax architecture, the main security threat is the device-level authentication mode. When this mode is utilized without certificate support, it is as vulnerable as MAC filtering and it can be exploited to launch MS or BS masquerading attacks. A less critical vulnerability is the DoS attack which can be launched by flooding authentication requests. This attack mostly affects the MS due to its limited processing resources, but it is not a major threat since it has a medium impact and a low motivation.

Confidentiality Evaluation

Wi-Fi includes some major vulnerabilities. It supports a null mode encryption which is configured as default in the majority of the commercial access points. WEP encryption can provide an elementary level of protection, but it is still too weak to keep the intruders out. WPA-PSK offers a satisfactory level of confidentiality, if long and complex keys are utilized. The ranking of the Wi-Fi confidentiality vulnerabilities is similar to authentication ranking, since both objectives are based on the same mechanisms.

UMTS incorporates strong encryption algorithms which have eliminated the deficiencies of its predecessor GSM. Nevertheless, the backwards compatibility with GSM can be exploited to compromise dual-band mobile devices by launching a man-in-the-middle attack. In this attack, the rogue BS can mandate the MS to use null mode encryption or one of the GSM encryption modes which can be easily broken (Biham & Dunkelman, 2000; Biryukov, Shamir, & Wagner, 2000). However, this is an unlikely attack since it requires the deployment of a BS and a prior successful launch of the IMSI hijack and AUTN capture attacks.

WiMax security architecture includes two main shortcomings. First of all, the DES encryption mode provides an inadequate level of confidentiality, since it can be easily broken. In addition, the eavesdropping of unencrypted management frames can be easily established, but it cannot greatly affect the system if robust authentication and integrity mechanisms have been deployed.

Integrity Evaluation

Wi-Fi supports null mode which leaves the messages totally unprotected against modification and replay attacks. WEP CRC-32 integrity mechanism provides a moderate level of protection, but there is no replay protection and the integrity protection can be overridden by an experienced attacker.

The UMTS architecture includes a major shortcoming, namely the inadequate replay protection of authentication tokens. This vulnerability can have a high impact since it allows the reuse of the token retrieved by an AUTH capture attack and the completion of the UMTS man-in-the-middle attack. However, it requires a prior successful launch of IMSI hijack and AUTN capture. Therefore it results in a high technical difficulty.

WiMax supports two modes that can greatly compromise information integrity. The first is the DES mode which does not support integrity and replay protection of data frames. The second is the null MAC mode for management frames, which can allow the intruder to inject modified management frames and affect the network operation.

Physical Layer Resilience Evaluation

The resilience of the physical layer of each technology is evaluated with respect to jamming and scrambling. Jamming is achieved by introducing a source of noise strong enough to significantly reduce the capacity of the channel. Scrambling is similar to jamming, but it takes place for short intervals of time and it is targeted to specific frames or parts of frames.

Wi-Fi comprises of the three different specifications IEEE 802.11a/b/g which all utilize random medium access techniques but operate on different physical channels. IEEE 802.11a/g operate on a 5 MHz OFDM channel, whereas IEEE 802.11b operates on a 5 MHz DSSS channel. The DSSS is more resilient to narrowband jamming than OFDM and therefore jamming has a higher impact

on IEEE802.11a/g. However, if the attacker wants to jam all the channels, the attacker has to jam a bandwidth of 40 MHz, which is quite difficult. Scrambling is easier to launch because of the random medium access layer.

UMTS operates on two 5 MHz DSSS channels, one for the uplink and one for the downlink. It is resilient to narrowband jamming because of the DSSS modulation, but it is still vulnerable to scrambling because of the random access.

WiMax operates on a 1.25-20 MHz OFDM channel and it employs TDMA techniques. Thus, it can be vulnerable to jamming especially if it operates on a narrow channel, but it is resilient to scrambling due to the TDMA.

OVERALL COMPARISON

The results from authentication, confidentiality, integrity, and physical layer resilience evaluation are presented in Table 2.

As follows, the overall comparison results:

- **Wi-Fi:**
  - **Authentication:** 6.75
  - **Confidentiality:** 6
  - **Integrity:** 6
  - **PHY Resilience:** 5
  - **AVERAGE RISK:** 5.94
- **UMTS**
  - **Authentication:** 4.5
  - **Confidentiality:** 3
  - **Integrity:** 3
  - **PHY Resilience:** 3.5
  - **AVERAGE RISK:** 5.94
- **WiMax**
  - **Authentication:** 6.5
  - **Confidentiality:** 6
  - **Integrity:** 7.5
  - **PHY Resilience:** 3
  - **AVERAGE RISK:** 5.75

Wi-Fi has the highest average risk, which is quite reasonable because of the initial lack of security mechanisms in the Wi-Fi specification and the subsequent failure of WEP. WPA and WPA2 modes are much more secure, but the poor usability and the limited security awareness have constrained their wide deployment. UMTS proved to be quite robust by eliminating the security inefficiencies of its predecessor GSM. However, an attacker can still exploit some backward-compatibility issues to launch a man-in-the-middle attack. WiMax's performance was not satisfactory enough mainly due to the provision of weak security modes. Nevertheless, the practical performance is greatly dependent on the actual security decisions of the network operators. These decisions vary according to the provided service requirements.

Table 2. Security evaluation

AUTHENTICATION EVALUATION				
Technology	**Threat**	**Likelihood**	**Impact**	**Risk**
Wi-Fi	Closed System	3	3	9
	MAC Filtering	3	3	9
	WEP	2	3	6
	WPA-PSK	1	3	3
Average Risk				**6,75**
UMTS	IMSI Hijack	2	3	6
	AUTN Capture	1	3	3
Average Risk				**4,5**
WiMAX	Device-level Authentication	3	3	9
	DoS on MS	2	2	4
Average Risk				**6,5**
CONFIDENTIALITY EVALUATION				
Technology	**Threat**	**Likelihood**	**Impact**	**Risk**
Wi-Fi	Null	3	3	9
	WEP	2	3	6
	WPA-PSK	1	3	3
Average Risk				**6**
UMTS	Rogue BS – Null / Weak	1	3	3
Average Risk				**3**
WiMAX	DES mode	3	3	9
	Management Frames	3	1	3
Average Risk				**6**
INTEGRITY EVALUATION				
Technology	**Threat**	**Likelihood**	**Impact**	**Risk**
Wi-Fi	Null	3	3	9
	WEP	1	3	3
Average Risk				**6**
UMTS	AUTN Replay	1	3	3
Average Risk				**3**
WiMAX	DES mode – Null integrity	3	2	6
	Management Frame-Null MAC	3	3	9
Average Risk				**7,5**
PHYSICAL LAYER RESILIENCE EVALUATION				
Technology	**Threat**	**Likelihood**	**Impact**	**Risk**
Wi-Fi	Jamming (IEEE 802.11a/g)	2	3	6
	Scrambling (IEEE 802.11a/g)	3	3	9
	Jamming (IEEE 802.11b)	2	2	4
	Scrambling (IEEE 802.11b)	3	2	6
Average Risk				**5**
UMTS	Jamming	1	2	2
	Scrambling	2	2	4
Average Risk				**2,5**
WiMAX	Jamming	1	3	3
	Scrambling	1	3	3
Average Risk				**3**

FUTURE TRENDS

Broadband wireless access networking is presently a rapidly evolving ICT area. Three important development trends can be identified:

- WiMax evolution for long range broadband wireless access.
- Development of a broadband wireless access technology supporting high speed mobility.
- Emerging 4G wireless cellular technology.

WiMax Evolution

The WiMax standard was finalized in June 2004. WiMax has the potential to change telecommunications as it is known today. "It eradicates the resource scarcity that has sustained incumbent service providers for the last century. As this technology enables a lower barrier to entry, it will allow true market-based competition in major telecommunications services like voice, video and data" (Ohrtman, 2005).

WiMax can offer a point-to-point range of 50 km with a throughput of 72 Mbps. The WiMax technology will make personal broadband services profitable to service providers and will be available to business and consumer subscribers at affordable prices. The first mobile WiMax products are expected to be introduced into the market in the first quarter of 2007. New technologies such as MIMO and beam forming for higher throughput and capacity will be introduced in 2007 (WiMax Forum, 2006).

Mobile Broadband Wireless Access (MBWA)

The IEEE 802.20 (or MBWA) Working Group was established in December 11, 2002, with the aim to develop a specification for an efficient packet-based air interface that is optimized for the transport of IP based services. The goal is to enable worldwide deployment of affordable, always-on, and interoperable BWA networks. The group will specify the lower layers of the air interface, operating in licensed bands below 3.5 GHz and enabling peak user data rates exceeding 1 Mbps at speeds of up to 250 km/h. A draft version of the specification was approved in January 18, 2006.

4G – Future Wireless Cellular Technology

Frameworks for future 4G networks, which seamlessly integrate heterogeneous mobile technologies in order to provide enhanced service integration, QoS, flexibility, scalability, mobility, and security, are currently being developed. However, these frameworks raise security vulnerabilities. An international consortium presents requirements and recommendations for the evolving 4G mobile networking technology (Akhavan, Vivek Badrinath, & Geitner, 2006). The 4G technology, which is at its infancy, is supposed to allow data transfer up to 100 Mbps outdoor and 1 Gbps indoor. The International Telecommunications Union (ITU) defines 4G as downlink throughput of 100 Mbps or more, and corresponding uplink speeds of at least 50 Mbps.

The 4G technology will support roaming for interactive services such as video conferencing. The cost of the data transfer will be comparatively low and global mobility will be possible. The networks will be all IPv6 networks. WLAN, 2.5G, 3G, and other networks such as SATCOM, WiMAX, and Bluetooth will be integrated in 4G networks. The antennas will be much smarter and improved access technologies like OFDM and MC-CDMA will be used. More efficient algorithms at the physical layer will reduce the inter-channel interference and cochannel interference.

Security Issues

Seamless convergence of heterogeneous wireless networks provides new security challenges for the research community. Global authentication architectures are needed which can operate independently of the wireless physical protocol. In addition, specifications are needed for maintaining the confidentiality and the integrity of the communication data while the user terminal is in a hand-off state. In this direction, a forum of mobile

operators called fixed mobile convergence alliance (FMCA) is working on defining specifications for the convergence of heterogeneous networks in the context of all IP 4G wireless systems.

Security policy issues are:

- The use of lightweight and flexible authentication, authorization, account, and audit (AAAA) schemes,
- The use of Trusted Computing (Reid, Nieto, & Dawson, 2003), and
- Different security polices for different services are recommended for 4G systems (Zheng, He, Xu, & Tang, 2005a).

Several security architecture proposals for 4G wireless systems have been made:

- Zheng, He, Yu, and Tang (2005b) propose a security architecture with:
  - Network access security features.
  - Network area security features for secure data exchange between network nodes.
  - User area security features for secure access to ME/USIM.
  - Application security for secure end-to-end data exchange.
- Integration of the SSL security protocol and a public key infrastructure is outlined and evaluated by Kambourakis, Rouskas, and Gritzalis (2004).
- A hierarchical trust model for 4G wireless networks is proposed by Zheng et al. (2005a).

CONCLUSION

In this chapter, the dominant mobile broadband technologies have been evaluated and compared based on their security performance. Three technologies were taken into consideration: Wi-Fi, UTMS, and WiMax. Their security architectures have been presented and analyzed in order to highlight the main security deficiencies. The evaluation and comparison methodology was based on assigning qualitative rankings to security threats with respect to the following criteria: likelihood, impact, and risk. The methodology was applied on four evaluation axes: authentication, confidentiality, integrity, and physical layer resilience. According to the comparison results, Wi-Fi is more liable to security attacks, followed by WiMax and UMTS. However, WiMax has not been widely tested under real-world systems due to its recent release. More security vulnerabilities may therefore be discovered in the future. Finally, the security architecture of UMTS is quite robust because of the lessons learned from GSM, but it is still not invincible against an experienced attacker with the right equipment.

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KEY TERMS

Authentication: Verification of the identity of a user or network node who claims to be legitimate.

Broadband: A network connection with a bandwidth of about 2 Mbps or higher.

Confidentiality: A cryptographic security service which allows only authorized users or network nodes to access information content.

EAP: Extensible authentication protocol (EAP) is an authentication protocol used with 802.1X to pass authentication information messages between a suppliant and an authentication server.

Integrity: A security service which verifies that stored or transferred information has remained unchanged.

UMTS: Universal mobile telecommunication system (UMTS) is a global third generation wireless cellular network for mobile telephony and data communication with a bandwidth up to 2 Mbps which can be upgraded up to 20 Mbps with high speed packet access (HSPA).

Wi-Fi: Wireless local area networking based on IEEE 802.11 standards.

WiMax: Wireless metropolitan area networking based on IEEE 802.16 standards.

WPA, WPA2: Wi-Fi protected access (WPA) is a protocol to secure wireless networks created to patch the previous security protocol WEP. WPA implements part of and WPA2 implements the entire IEEE 802.11i standard. In addition to authentication and encryption, WPA also provides improved payload integrity.

Chapter XLIX
Extensible Authentication (EAP) Protocol Integrations in the Next Generation Cellular Networks

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ABSTRACT

Authentication is an important part of the authentication authorization and accounting (AAA) schemes and the extensible authentication protocol (EAP) is a universally accepted framework for authentication commonly used in wireless networks and point-to-point protocol (PPP) connections. The main focus of this chapter is the technical details to examine how EAP is integrated into the architecture of next generation networks (NGN), such as in worldwide interoperability for microwave access (WiMAX), which is defined in the IEEE 802.16d and IEEE 802.16e standards and in current wireless protocols, such as IEEE 802.11i. This focus includes an overview of the integration of EAP with IEEE 802.1x, remote authentication dial in user service (RADIUS), DIAMETER, and pair-wise master key version (2PKv2).

INTRODUCTION

Extensible authentication protocol (EAP) is a universally accepted authentication mechanism, frequently used in different wireless technologies. Although the applications of EAP protocol are not limited to wireless local area networks (LANs), they could be used for authentication in wired-based LAN applications. However EAP is most often used in wireless LANs. The integrations of EAP and other security protocols and mechanisms often result in strong security frameworks.

These integrations are often established with other security protocols and mechanisms, such as transport layer security (EAP-TLS), message digest 5 (EAP-MD5), privacy key management (PKM-EAP), and so forth.

The organization of the sections of this chapter is as follows: Section II will discuss details about the EAP-IEEE 802.1x interactions. Section III is dedicated to remote authentication dial in user service (RADIUS) and DIAMETER in the authentication/authorization schemes. Section IV talks about the IEEE 802.1x-EAP functions implemented in Wi-Fi (IEEE 802.11i) and introductions to EAP-MD5, lightweight extensible authentication protocol (LEAP), EAP-TLS (TTLS) and protected extensible authentication protocol (PEAP). Section V presents the PKMv2-EAP scheme in worldwide interoperability for microwave access (WiMAX) (IEEE 802.16) followed by section VI, which is a configured testbed for a WiMAX system. Sections VII and VIII contains conclusions and references respectively.

EAP AND IEEE 802.1X

Based on RFC 3748 (Aboba, Blunk, Vollbrecht, Carlson, & Levkowetz, 2004), EAP runs on top of IEEE 802.1x (Figure 1), therefore 802.1x is the key issue to understanding the EAP. IEEE 802.1x offers a strong framework for authenticating and controlling user traffic for protecting networks. IEEE 802.1x also offers dynamically varying encryption keys. IEEE 802.1x uses EAP in both wired and wireless LANs and supports multiple authentication methods, such as Kerberos, one-time passwords, and public key certificates. Our main focus is on wireless technologies.

IEEE 802.1x initially starts the communications by an attempt to connect with an authenticator (i.e., an 802.16 or 802.11 access point [AP]) to authenticate an unauthenticated supplicant. The AP responds back by enabling a port for passing only EAP packets between the clients to the authentication server, which is usually located on the wired side of the AP. The AP blocks all other traffic (i.e., HTTP and dynamic host configuration protocol [DHCP] packets), until the AP (authenticator) is able to verify the client's identity using an authentication server (e.g., DIAMETER or RADIUS). Once authenticated, the AP opens the client's port for the rest of traffic types.

To better understand how 802.1x operates, the interactions mentioned in Table 1a usually happen between various 802.1x elements.

As showed in Figure 1, EAP is an important component of an 802.1x-based infrastructure. EAP improves the authentication scheme provided by the point-to-point protocol (PPP) (RFC 1661). EAP provides PPP with a generalized framework for

Figure 1. 802.1x authentication components (Adapted from Kwan, 2003)

Figure 2. Different layers of 802.1x (Adapted from Leira, 2005)

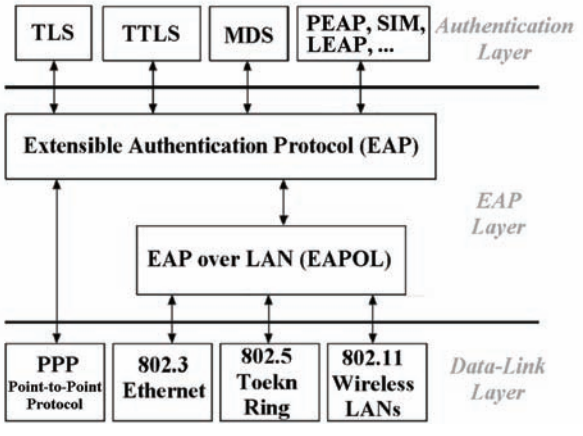


Table 1a. A summary of EAP messages in a supplicant-authenticator-authentication server scenario

	SUPPLICANT	AP (ACCESS POINT) AUTHENTICATOR	AUTHENTICATION SERVER
1.	Sends EAP-start message →	Receives the message	
2.		← Replies with an EAP-request ID	
3.	EAP-response with ID →		Verifies the client's identity using Digital Certificates, etc
4.		Receives Accept/Reject message	← Sends Accept/Reject to the AP
5.	Receives Accept/Reject note	← Sends Accept/Reject notification	
6.	If accepted, port is open And messages are accepted	→	AP forwards the messages to the Authentication Server
7.	If rejected, the end		

various types of authentication schemes (Chen & Wang, 2005). The 802.1x standard includes a definition of EAP encapsulation for Ethernet packages used over LANs, which is called EAP over LAN (EAPOL). Figure 2 (Leira, 2005) shows various layers of selective authentication and network type 802.1x.

There are three main components found in 802.1 X-based systems:

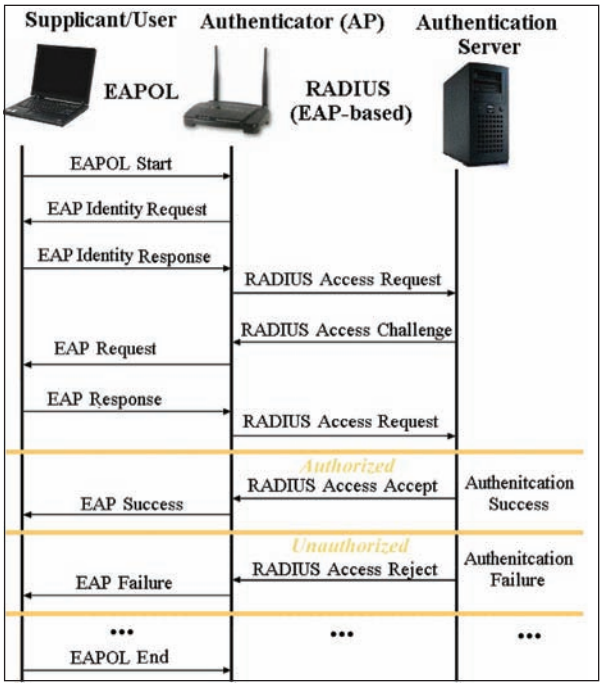
- Supplicant, which is the client/user
- Authenticator, which is the mediator between the client and the Authenticator Server
- Authenticator Server, which determines if the client (supplicant) has the correct information for authentication. This could be a RADIUS or a DIAMETER server

In most cases, both supplicant and the authentication server have relatively more processing capabilities than the authenticator. The authenticator is mostly responsible for forwarding, therefore it requires less power as compared to the other two components. An AP can serve well as the role of an authenticator, which makes the system well suited for wireless networks.

Figure 3, which has more details compared to Table 1a, shows how the communication between the supplicant, authenticator, and the authentication server works. Initially the authenticator blocks all traffic except for the EAPOL-based traffic. The rest of the communication process is similar to that of Table 1a. As shown in Figure 3, the EAP scheme operates in the following fashion (Piscitello, 2005) (see Box 1).

In a true end-to-end secure wireless network, it is not only crucial that the authenticator and authentication server ensure user's legitimacy, but also the supplicant has to be confident that the authentication server and the authenticator are legitimate and not spoofing devices who try to

Figure 3. The supplicant-authenticator-authentication server relationship



Box 1.

#	Process Taking Place	Message Transmitted/State
1.	Supplicant tries to connect to the authenticator (AP)	802.1x Associate Request
2.	Authenticator detects supplicant and enables client's port	Port set to Unauthorized
3.	Authenticator returns a response to supplicant and waits	802.1x Associate Response
4.	Supplicant transmits a message to authenticator	EAP-START
5.	Authenticator replies a message to supplicant, asks for identity	EAP-REQUEST IDENTITY
6.	Supplicant provides its identity to authenticator	EAP-RESPONSE
7.	Authenticator forwards EAP-RESPONSE to authentication server	FORWARD EAP-RESPONSE
8.	Authentication server authenticate clients	Authenticates via EAP-TLS, LEAP
9.	If accepted by authentication server, signals to authenticator	ACCEPT
10.	If rejected by authentication server, signals to authenticator	REJECT
11.	If authenticator receives acceptation, responds to supplicant Supplicant can use the wireless LAN	EAP SUCCESS Port set to AUTHORIZED
12.	If authenticator receives rejection, responds to supplicant Supplicant remain blocked from the wireless LAN	EAP FAILURE Port state no change
13.	If client succeeded, authenticator passes global key to client	Global Key Passed
14.	When client terminates session, it logs off	EAP LOGOFF

obtain the user name and password from the user. This scenario can be prevented by using a mutual authentication scheme where the authentication server and the authenticators also have to be authenticated by the supplicant. Examples of such mutual authentication schemes are used in TLS, tunneled TTLS (TTLS), LEAP, and PEAP.

IEEE 802.1x also provides a framework to reduce or eliminate the danger of session hijacking and man-in-the-middle (MITM) attacks, however it requires that the right type of authentication (mutual authentication) be used. Secure authentication does not yet imply secure communication. A strong encryption method is required to ensure data confidentiality. EAP enables the usage of different types of encryption with dynamic key distribution techniques.

RADIUS AND DIAMETER

Both RADIUS (Hill, 2001) and DIAMETER (Calhoun, Loughney, Guttman, Zorn, & Arkko, 2003) are authentication, authorization, and accounting (AAA) protocols for applications and mechanisms used in network access or Internet protocol (IP) mobility. They are intended to work in both local and roaming situations.

Many applications running through ISPs using modems, DSL, cable, or wireless connections require some sort of user name/password for access permission. This information is usually transmitted to a RADIUS server, over a network access server (NAS) device using the point-to-point protocol (PPP) and the RADIUS protocol. The RADIUS server verifies that the information is correct. This is done using authentication schemes, such as, password authentication protocol (PAP), challenge handshake authentication protocol (CHAP), or EAP. If authentication and authorization are accepted, then the server will authorize access to the ISP network and select an IP address and other access control parameters (L2TP parameters).

The RADIUS server is also notified of any session start-stop for related accounting, billing, and other statistical issues. RADIUS is an extensible

protocol in which most RADIUS vendors have their own hardware and software implements.

The DIAMETER protocol is proposed to replace RADIUS and it is designed to be backward compatible in most cases. The main differences between DIAMETER and RADIUS protocols are, (see Box 2).

The message format and the authentication flows in DIAMETER EAP applications are given in Figures 4 and 5.

Applying RADIUS to Wireless LANs

In wireless-based networks that use 802.1x port access control, the wireless station is a remote user and the wireless AP behaves as the network access server (NAS) (Phifer, L 2., 2003). The IEEE 802.11-based protocols (a, b, or g) are used to associate the wireless stations to the wireless APs.

Once the client is associated, it transmits an EAP-Start message to the AP. The AP sends a request to the wireless station, asking for its identity and relays the message to an AAA server using a RADIUS-based access-request user name message.

As expected, through the AP, the wireless station and the AAA server establish the authentication process by exchanging RADIUS access-challenge and access-request messages. According to the specific EAP type, an encrypted TLS tunnel could be used to convey the messages inside of the tunnel.

If an access-accept message is sent by the AAA server, the wireless station and the AP establish a handshake. This generates session keys that are used by either temporal key integrity protocol (TKIP) or wired equivalence privacy (WEP) to encrypt data. At this point, the port is unblocked by the AP and the wireless station is able to send and receive data to and from the attached LAN.

If an access-reject message is sent by the AAA server, the client will be disassociated by the AP.

Box 2.

#	DIAMETER uses:	RADIUS uses:
1.	Reliable transport protocol (TCP or stream control transmission protocol [SCTP])	Uses an unreliable transport protocol (UDP)
2.	End-to-end transport level security protocols (IPSec or TLS)	End-users, such as, CHAP and PAP
3.	Transition support for RADIUS	No direct compatibility with DIAMETER
4.	Large address space for AVPs (attribute value pairs) – 32 bits	Smaller address space – 8 bits
5.	A peer-to-peer protocol scheme Server-initiated messages support	Client-server protocol scheme Request/response scheme only
6.	Both stateful and stateless models	Only a stateless model
7.	DNS (dynamic name system), SRV (generalized service location), and NAPTR (naming authority pointer), for dynamic discovery of peers	Static Discovery agents
8.	Capability Negotiation (version, applications, etc)	No such built-in capability
9.	Application layer acknowledgements and built-in Failover (device-watchdog request/ device-watchdog answer [DWR/DWA])	No such failover mechanism
10.	Error notification	No such notification
11.	Better roaming support	Average support for fixed and roaming users
12.	Better extended command and attributes	Average command and attributes
13.	Better Mobile-IP supports and stronger security	Average security options

Figure 4. DIAMETER message format (Adapted from Wu, Chen, Chen, & Fan, 2005)

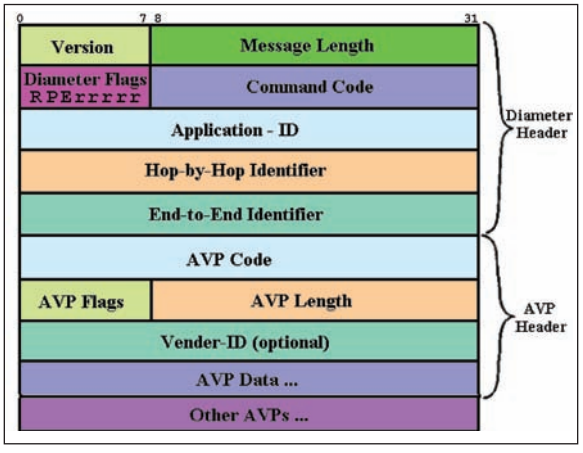
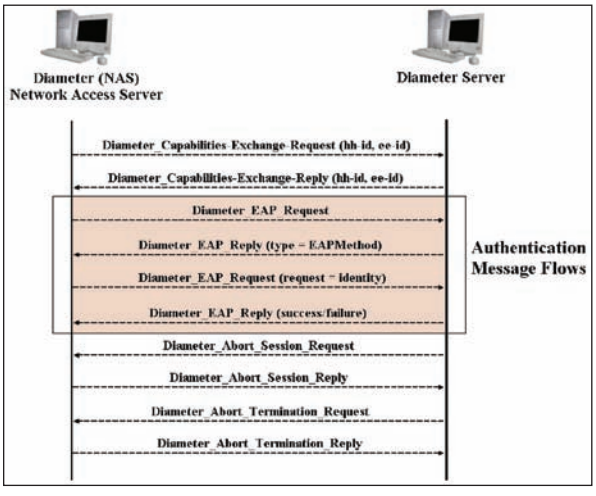


Figure 5. Authentication flows in diameter EAP applications (Adapted from Wu, Chen, Chen, & Fan, 2005)



At this point, the failed supplicant can try the authentication process again, however it is prevented by the AP from data packet transmissions. It should be noted that the failed client is still able to listen to the transmitted data across the wireless channel. This raises the importance of encryption techniques for privacy over the air.

The AAA server uses the attribute-value pairs, which are included in the RADIUS messages. This is to deliver session parameters to the wireless station via the AP, such as, session-timeout or VLAN tag (Tunnel-Private-Group-ID=tag, Tunnel-Type=VLAN). The additional information, which can be delivered and used, depends on the AAA Server, AP, and the wireless station settings.

EAP and Different Authentication Methods

EAP by itself cannot protect the authentication message exchange between the client, authenticator, and authentication server. In order to secure the message exchange, an EAP authentication protocol is necessary. The commonly used EAP authentication protocols include (Kwan, 2003; Phifer, 2003; "What are Your EAP Authentication Options?," 2005):

EAP-MD5 (RFC 1994): The EAP-MD5 protocol lets a RADIUS server authenticate LAN stations through MD5 hash verification for each user/password. For a trusted Ethernet, this is a simple and reasonable choice where there is little risk of an outsider active attack or sniffing. EAP-MD5, on the other hand, is not suitable for wireless LANs or public Ethernets, since the station identities and password hashes are prone to easy outside sniffing. A man-in-the-middle attack or session hijacking could also be an issue. EAP-MD5 is able to protect the message exchange flow through creating a unique digital signature," which authenticates each packet using this to ensure authenticity for the EAP messages. EAP-MD5 has light computational weight and this increases it's timing performance, which makes it fairly easy to implement and configure. EAP-MD5 does not use public key infrastructure (PKI) certificates for validating clients nor does it provide strong encryption for protecting the authentication messages between the supplicant and the authentication server. EAP-MD5 is most suitable for the EAP message exchanges in wired networks where the EAP client is directly connected to the authenticator. In this case, the chances for message interception and eavesdrop-

ping are relatively very low. Therefore for wireless 802.1x authentication schemes, stronger and more robust EAP authentication protocols should be deployed.

EAP with transport layer security (EAP-TLS): EAP-TLS is discussed in RFC 2716, which is the only secured standard option (along with EAP-TTLS) designed for wireless LANs. EAP-TLS mandates a procedure in which the station and the RADIUS server are both required to prove their identities using public key cryptography (i.e., security tokens, smart-cards, or digital certificates). This procedure is secured by an encrypted TLS tunnel, which makes EAP-TLS very resilient to against dictionary, man-in-the-middle, and other types of attacks. However, the station's identity, which is the name attached to the certificate, can still be sniffed through eavesdropping. EAP-TLS is a very attractive candidate for large enterprises, which only use Windows (2000/2003/XP)-based applications with deployed certificates. EAP-TLS provides strong security schemes by requiring both client and authentication server (mutual authentication) to be authenticated and authorized by using PKI certificates. This works well within 802.1x authentication schemes as the TLS tunnel between the client and the authentication server protects the EAP messages from sniffing and eavesdropping. The only notable drawback of EAP-TLS is the requirement of PKI certificates on both sides (clients and authentication servers). This causes complications in roll-out and maintenance procedures and increases the amount of overhead to establish a secure link as certificates can be quite large. Figure 6 shows the EAP-TLS message flow.

EAP with tunnelled TLS (EAP-TTLS): EAP-TTLS is an extension of EAP-TLS, which provides the benefits of a strong encryption scheme without the complexity of mutual certificates on both sides (client and authentication server). Similar to the EAP-TLS scheme, EAP-TTLS scheme supports mutual authentication, however it only requires the authentication server to be validated to the client using a certificate exchange. EAP-TTLS allows the client to be authenticated by the authentication server through a user name/password process and only requires a certificate used by the authentication server. EAP-TTLS simplifies the roll out and maintenance procedures while retaining strong security and relatively strong authentication scheme. A TLS tunnel is used for protecting EAP messages and for reusing existing user credential services for 802.1x authentication, such as RADIUS, active directory, and LDAP. AP-TTLS also provides backward compatibility for other authentication protocols, such as, PAP, CHAP, MS-CHAP, and MS-CHAP-V2. If TLS tunnels are not used, EAP-TTLS is not considered secure and can be fooled into revealing identity credentials. EAP-TTLS is most suitable for infrastructures that require strong authentication without mandating the use of mutual certificates. Wireless 802.1x authentication schemes usually support EAP-TTLS.

Protected EAP (PEAP): PEAP is an Internet-draft (still not an RFC), which is similar to EAP-TTLS in terms of supporting mutual authentication. PEAP is currently being supported by Cisco Systems, RSA Data Security Inc., and Microsoft. PEAP is an authentication protocol alternative to EAP-TTLS, which overcomes EAP weaknesses through:

a. Protecting user credentials
b. Securing EAP negotiation flows
c. Standardizing key exchange flows
d. Supporting fragmentation and reassembly procedures
e. Supporting fast reconnects

PEAP allows the utilization of other EAP-based authentication protocols and securing the transmission through utilizing a TLS encrypted tunnel. PEAP relies on the TLS keying method for the key creation and exchange mechanisms. The PEAP client is authenticated directly with the back-end authentication server. The authenticator acts as a pass-through device, which does not require much processing power or manipulation and needs little understanding of the EAP authentication protocol mechanism. Unlike EAP-TTLS, PEAP does not support inherent username and password authen-

tication against an existing user (unlike LDPA). To support this, every specific vendor has its own feature built on top of the protocol. PEAP is most suitable for infrastructures, which require strong authentication without the use of mutual certificates, similar to EAP-TTLS. Wireless 802.1x authentication schemes usually support PEAP.

Cisco's lightweight EAP (LEAP): LEAP goes beyond EAP-MD5 in addressing the security issues of wireless networks by delivering the keys used for WLAN encryption and requiring mutual authentication. Mutual authentication reduces the risk of an attacker posing as an AP (MITM attack). However, station identities and passwords remain vulnerable to dictionary sniffing attacks. LEAP is mostly used when Cisco-based APs and cards are involved. LEAP mandates mutual authentication between the client and the authenticator. The client first has to authenticate itself to the authenticator and then the authenticator should authenticate itself to the client. If the two authentication procedures are done successfully, a network connection is granted. Unlike EAP-TLS, LEAP is username/password-based and is not based on PKI certificates. This simplifies roll-out and maintenance procedures. Being the proprietary to Cisco is one of the drawbacks of LEAP, which is the reason it has not been widely adopted by other networking vendors. LEAP is most suitable for wireless scenarios that support Cisco AP's and LEAP compliant wireless NIC cards.

EAP-SIM: The EAP method for global system for mobile communications (GSM) subscriber identity module (SIM), or EAP-SIM, is an EAP-based mechanism used for authentication and session key distribution, which is used in the GSM-SIM. EAP-SIM is described in RFC 4186.

Tables 1b and 2 show summaries and comparisons between all mentioned EAP-based protocols.

Depending on the specific EAP authentication protocol used, IEEE 802.1x authentication protocol can help to solve the following security issues (Kwan, 2003):

- **Dictionary attack:** In this type of attack, the attacker obtains the challenge/response message exchange from a password authentication session and uses a brute force mechanism to find the password. IEEE 802.1x solves this type of attack by using TLS-based tunnels for protecting credential exchanges among authenticator and supplicant.
- **Session hijack:** In this attack, the attacker is able to sniff the packets passed between the client and the authenticator and to recover the client's identity information. This pushes the "legitimate" client out of the scope through a form of denial-of-service (DoS) attack and impersonates the client to continue the conversation with the authenticator (DoS and session hijacking). IEEE 802.1x can thwart the session hijacking through its ability to securely authenticate with dynamic session-based keys.
- **Man-in-the-middle:** The MITM attack happens in one-way authentication or unbalanced schemes, where the attacker obtains the necessary information from the client and/or

Table 1b. Comparison between different EAP methods in terms of client/server strength (Adapted from Phifer, 2003)

	EAP-MD5	EAP-TLS	EAP-TTLS	LEAP	PEAP
Supplicant Authentication	Password Hash	Public Key (Certificate or Smart Card)	CHAP, PAP, MS-CHAPv2, EAP	Password Hash	Any EAP, Public Key, or EAP-MS-CHAPv2
Server Authentication	None	Public Key (Certificate)	Public Key (Certificate)	Password Hash	Public Key (Certificate)
Dynamic Key Delivery	No	Yes	Yes	Yes	Yes
Security Risks	Identity exposure, Dictionary attack, Man-In-The-Middle (MitM) attack, Session hijacking	Identity exposure	Man-In-The-Middle (MitM) attack	Identity exposure, Dictionary attack	Man-In-The-Middle (MitM) attack

the authenticator and comes in the middle of the session and becomes the "middle man." Through IEEE 802.1x's authentication and dynamic session-based keys, the encryption of the data stream between the client and authenticator can prevent this type of attack.

IEEE 802.11I - WLAN SECURITY STANDARD IMPLEMENTATION

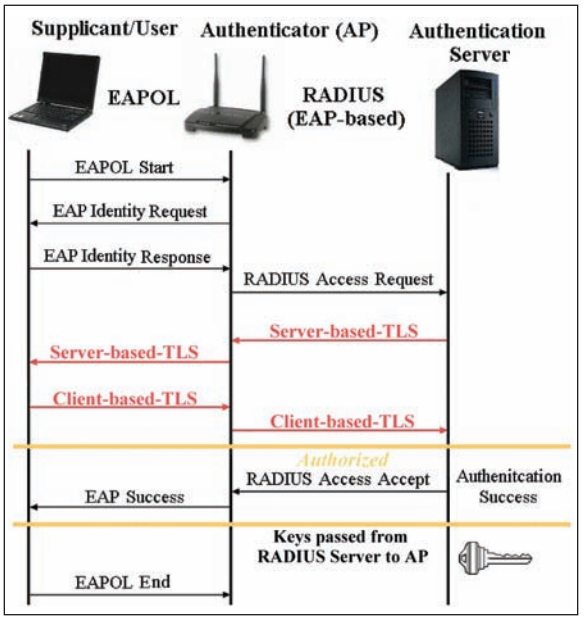
The IEEE 802.11i standard was designed to provide secure communications in wireless LANs, which is part of the IEEE 802.11 specifications. For many years, WEP was used as a WLAN security technology. However, WEP has been proven not to be secure with today's computational power due to the short period of the stream cipher used and how key stream reuse allows the data to be recovered (to name a few). IEEE 802.11i enhances the encryption, authentication, and key management schemes of WEP. IEEE 802.11i is based on a strong security scheme, the Wi-Fi protected access (WPA).

WPA in 802.11i

WPA is a subset of IEEE 802.11i, the standard for WLAN security, and consists of the followings:

- An authentication mechanism that uses IEEE 802.1x or pre-shared keys scheme.
- An encryption mechanism, which uses temporal key integrity protocol (TKIP), per IEEE 802.11i definition. TKIP could be software-based offered by products that support WEP.

Figure 6. Message flow of EAP-TLS



WPA2 and 802.11i

WPA2 is the second generation of WPA security introduced by the Wi-Fi Alliance (Lehembre, 2005). It is consisted of:

- An authentication mechanism that uses IEEE 802.1x or pre-shared keys scheme.
- An encryption mechanism, which uses advanced encryption standard (AES), per IEEE 802.11i definition.

WPA2 with AES is eligible for FIPS 140-2 (specified by the United States Government's National Institute of Standards and Technology [NIST] and uses four level of securities) compli-

Table 2. Comparison among various EAP methods in terms of wireless security strength (Adapted from "What are Your EAP Authentication Options?," 2005)

Protocol	The Implementation Procedure	Authentication Attributes	Deployment Difficulty	WEP Key Generated?	Wireless Security
EAP-MD5	Challenge-based password authentication	One-way	Easy	No	Poor
EAP-TLS	Certificate-based, two-way authentication (mutual)	Two-way (Mutual)	Difficult	Yes	Excellent
LEAP	Username/hashed password authentication	Two-way (Mutual)	Easy	Yes	Good, if strong passwords are used
PEAP or TTLS	Server authentication via certificates, client via other methods	Two-way (Mutual); Identity hiding (opt)	Moderate	Yes	Better than that of EAP-MD5

ance. WPA2 is a requirement for Wi-Fi compliance from 2006.

EAP Method Requirements for Wireless LANs

RFC 4017 (Stanley, Walker, & Aboba, 2005) specifies the requirements for EAP methods used in IEEE 802.11-based systems, which uses IEEE 802.11i for authentication and authorization. This in turn could be applied to IEEE 802.16 as well. 802.11i MAC security enhancements makes use of both IEEE 802.1x and EAP. Today's deployments of IEEE 802.11 wireless LANs are based on EAP, integrated with several EAP methods, namely: EAP-TLS, EAP-TTLS, PEAP, and EAP-SIM, which were discussed before. These methods support authentication credentials, including *digital certificates*, *secure tokens*, *usernames/passwords*, and *SIM secrets*.

IEEE 802.11i specifies the usage of EAP for both authentication and key exchange among the EAP peers and servers. RFC 3748 (RFC 3748 - EAP) outlines the EAP usage within IEEE 802.11i, which is subject to threats, given that WLAN provides ready access to any attacker within range.

The following four components are integral parts of IEEE 802.11i specifications (IEEE 802.11i: WLAN Security Standards," 2006):

- **Temporal key integrity protocol (TKIP):** TKIP is a protocol which uses an RC4 cipher for encryption of data and deals with confidentiality of data. TKIP improves the security weaknesses of WEP. It uses a message integrity code, called "TKIP-Michael algorithm," which authenticates end devices for legitimacy. TKIP utilizes a mixing function to overcome weak-key and brute-force attacks. TKIP is used in 802.11i during two phases:
  - **First phase:** In the first phase, TKIP is used together with an improved message integrity check (MIC). This is to stop data manipulation.
  - **Second phase:** In the second phase, TKIP and MIC are replaced with counter with cipher block chaining message authentication code (CCMP). CCMP uses the AES encryption scheme.

  TKIP offers three advantages over WEP:
  - Longer initialization vector (IV), which minimizes the chance session key reuse
  - Key hashing, which results in a different key used for each data packet
  - MIC, which ensures that the message is not altered during the communication between sender and receiver
- **Counter-mode/CBC-MAC protocol (CCMP):** CCMP is similar to TKIP, in which it deals with the confidentiality of data, as well as authentication and encryption. One of the differences between CCMP and TKIP is the fact that CCMP uses AES in counter mode for data confidentiality. The other difference is the usage of cipher block chaining message authentication code (CBC-MAC) for authentication and integrity. In the architecture of 802.11i, CCMP uses a 128-bit key scheme. CCMP provides protections for some fields, which are not encrypted through a mechanism, which is so-called additional authentication data (AAD). AAD protection includes a scheme which prevents attackers from replaying packets to various destinations.
- **IEEE 802.1x:** IEEE 802.11i is a wireless implementation of 802.1x, which offers an effective framework to authenticate and control user traffic and also offers dynamically varying encryption keys. Through this component (802.1x), 802.11i is able to get tied to EAP.
- **EAP encapsulation over LANs (EAPOL):** As discussed in Figure 2, EAP layer covers EAPOL, which is a key protocol in IEEE 802.1x for key exchange. Two main schemes covered in the EAPOL-key exchanges are defined in IEEE 802.11i, which are the 4-way handshake and the group key handshake.

PKMV2-EAP SCHEME IN WIMAX (IEEE 802.16)

WiMAX (IEEE 802.16) stands for worldwide interoperability for microwave access, which is maintained by the WiMAX Forum. WiMAX has similarities with Wi-Fi; however it claims to achieve higher bandwidth (up to 70 Mbps) over a 70 mile (+110 km) range, which outperforms Wi-Fi. There are also some similarities between the security schemes between WMAX's and IEEE 802.11i.

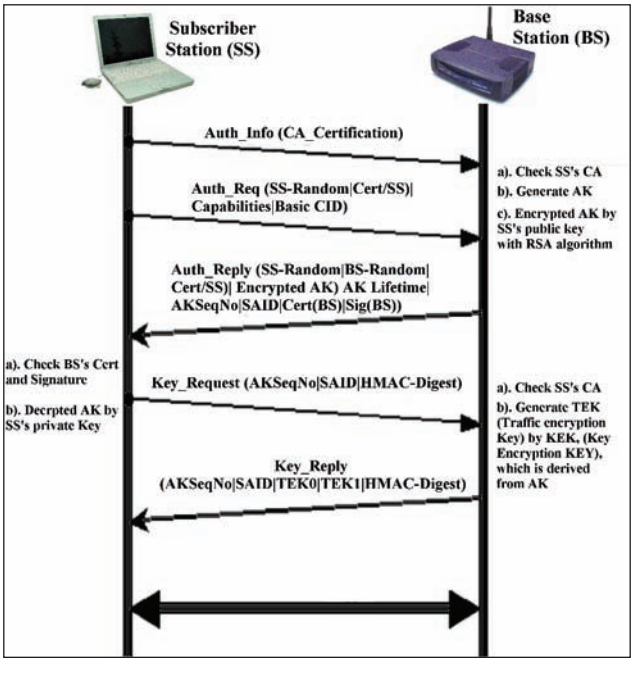
In this section, the security mechanisms for WiMAX are described. For an end-to-end authentication scheme, WiMAX uses extensible authentication protocol with privacy key management (EAP-PKM), which relies on the transport layer security (TLS) standard and public key cryptography ("WiMAX Technology," 2005). PKM is a protocol, which uses the Rivest, Shamir, and Adleman (RSA) public-key scheme, X.509 digital certificates, and a strong encryption scheme for the subscriber station (SS)-base station (BS) interactions. There are two PKM protocols supported in the IEEE 802.16 standard; PKM version 1 (PKMv1) and PKM version 2 (PKMv2). PKMv1, which is a one-way authentication method, is proven to be prone to variety of attacks and is not covered in this chapter. PKM supports two authentication protocol mechanisms:

1. RSA public key-based certificates, mandatory in all devices
2. EAP

Authorization via PKM RSA Authentication Protocol

Figure 7 shows the authorization and authentication processes of PKMv2 protocol using a request/grant access method. For a SS (PKM client) to have access to the BS network, the PKM server has to authorize the connection and the SS also needs to authenticate the BS; after that, the SS will have security features enabled. Once the SS associates with the BS, the SS shares a private encryption key with the BS and communication between

Figure 7. PKMv2 authentication and authorization process (Adapted from Adibi, Bin, Ho, Agnew, & Erfani, 2006)



the BS and SS can be initiated using encrypted messages.

Authorization via PKM Extensible Authentication Protocol

After the SS is associated to the BS, the EAP authorization procedure starts. Figure 8 shows the EAP authorization and authentication flow steps:

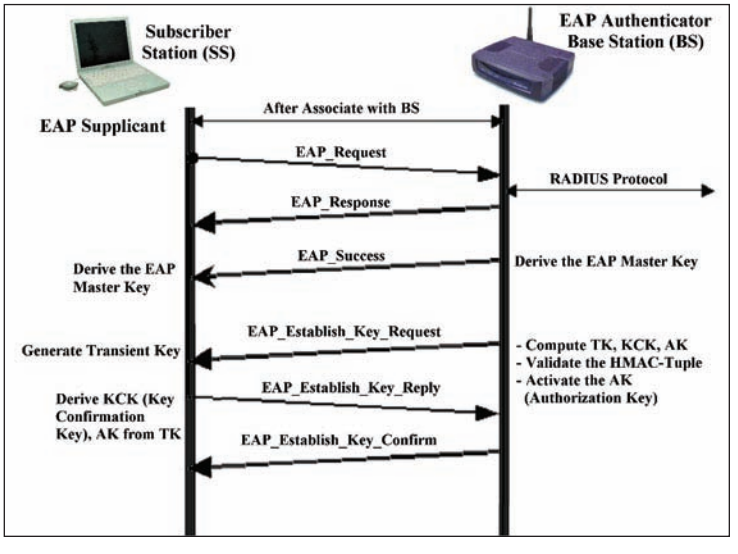
Security Analysis of WiMAX Authentication

The EAP-PKM is intended to secure WiMAX clients and servers in a more robust way. The following list summarizes the strength of EAP-PKM:

1. PKMv2 supports mutual authentication, which can prevent man-in-the-middle attacks.
2. The X.509 digital certificate issued for each SS is unique and cannot be easily forged.
3. Each service has a unique security association identifier (SAID), therefore if one service is compromised, the other services are not affected.
4. The limited lifetime of authorization key (AK) provides key-refresh and periodic reauthorization, which prevents attackers from gathering enough data to launch cryptanalysis.
5. To correct replay attacks, it is recommended to add a random value transmitted from BS and SS for SA authorization.
6. WiMAX security supports two strong encryptions algorithms; triple data encryption standard (3DES) and AES, which are considered leading edge (AES in particular).
7. The ability of an SS to cache or transfer the master key to avoid a full reauthentication procedure.
8. EAP-PKM relies on the TLS standard that is based on public key cryptography, which is costly for some wireless vendors. Therefore, a high performance security processor is dedicated to BS in WiMAX, which enables the implementation of a complicated authentication system in WiMAX.

In this section, a WiMAX-based authentication using EAP-TLS and EAP-PKM were presented. This included the PKMv2 handshaking schemes. It is believed that WiMAX possesses more extensive security power compared to the ones in Wi-Fi, which in turn will favor WiMAX in the comparative market share.

Figure 8. 802.16e EAP authentication process (Adapted from Adibi et al., 2006)



CONCLUSION

In this chapter, to help address the security issues of unauthorized access, The development of IEEE 802.1x was to provide a standard authentication mechanism in port-based scenarios. EAP, on the other hand, offers supports to a variety of standard authentication messaging protocols. EAP provides multivendor solutions to support network authentication framework. Additional EAP types, including EAP-SIM and EAP-SecurID (which supports hardware tokens), are also defined. EAP specifies the method in which supplicant/authenticator/authentication server interact and the type of standard messaging exchanged between them. EAP, however does not specify the actual authentication protocol. Therefore, EAP's advantages can be summarized as:

- EAP permits multiple authentication protocols without extra setup steps.
- EAP is flexible and supports multiple authentication protocols without the necessity of requiring to match an authenticator to a specific authentication mechanism. EAP permits the authentication server to selects the best suitable authentication protocols, which is supported on the client, as well as itself. This is usually done without the need for fully configuring the authenticator with the authentication protocol. In this scenario, the authenticator acts as a pass-through device (pass-through is optional).
- The authenticator has the ability to act as a pass-through device for non-local clients and at the same time, authenticate local clients using authentication protocols it may not support locally.
- The existence of a separate authenticator and authentication server operating in the pass-through mode, permits simplifications of the credentials and development of standard messaging protocols. The authenticator is responsible for determination of the outcome of the authentication from the access-accept or reject message provided by the authentication server. The outcome of the authentication is not affected by the EAP packet's contents. This may pose as vulnerability manipulations and different attacks. Throughout this chapter, where appropriate, the application of EAP using different authentication/authorization methods for wireless applications, were discussed. Special attention was given to EAP-TLS and EAP-PKMv2 for 802.16e systems.

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KEY TERMS

AP: Access point (or wireless access point) is a device that connects wireless devices (i.e., mobile users [MUs], laptops, etc.) together. APs are usually connected to another device called wireless controller (WC). A wireless network is usually comprised of a WC and a few APs, servicing MUs.

DIAMETER: DIAMETER is an authentication, authorization, and accounting (AAA) protocol, an updated version of RADIUS.

DHCP: Dynamic host configuration protocol is a protocol that automatically manages (temporarily assign and release) IP addresses to devices on the network (wireless and wired).

EAP: Extensible authentication protocol is a universally famous authentication protocol accepted framework for authentication. Its integration with other security schemes usually produces strong frameworks for various wireless and wired applications.

MD5: Message-digest algorithm 5 is a 128-bit hash function, which is a widely used cryptographic element. MD5 has shown some weaknesses; therefore it is not counted a robust scheme nowadays.

PEAP: Protected EAP is a security method which transmits authentication information, including passwords. PEAP can be used in variety of scenarios including wireless and wired topologies.

PKM: Privacy key management is a private key scheme used with EAP and TLS for providing end-to-end security schemes for wireless technologies.

RADIUS: Remote authentication dial in user service is an AAA protocol that works in a client/server application scenario. RADIUS oversees the authentication and authorization scheme of the session established between two entities. It is further updated by DIAMETER.

TLS: Transport layer security is used mostly in client/server applications, which require endpoint authentication and communications privacy, particularly over the Internet. This is mostly done using cryptographic measures.

WiMAX: WiMAX stands for worldwide interoperability for microwave access, which has been defined by the WiMAX Forum, formed in 2001. WiMAX is also known as IEEE 802.16 standard, officially titled WirelessMAN and is an alternative to DSL (802.16d) and cellular access (802.16e).

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