A Survey on Applied Cryptography in Secure Mobile Ad Hoc Networks and Wireless Sensor Networks

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ABSTRACT

Many secure mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs) use techniques of applied cryptography. Numerous security routing protocols and key management schemes have been designed based on public key infrastructure (PKI) and identity-based cryptography. Some of these security protocols are fully adapted to fit the limited power, storage, and CPUs of these networks. For example, one-way hash functions have been used to construct disposable secret keys instead of creating public/private keys for the public key infrastructure. In this survey of MANET and WSN applications we present many network security schemes using cryptographic techniques and give three case studies of popular designs.

INTRODUCTION

This chapter aims to explain how MANET and WSN security design may be improved with a broad knowledge of cryptography. Securing MANETs and WSNs requires consideration of the following factors: dynamic topologies, resource constraints, no infrastructure, and limited physical security. Because WSNs typically have more nodes and less power than MANETs, their security design requires more attention to computational capabilities and memory resources. Much cryptographic, authentication, and authorization research has been conducted into the details of secure routing, key management, and trust management in MANETs and WSNs.

Previous researches have studied attacks and countermeasures in MANETs (Wu & Chen, 2008), key management in MANETs (Wu & Cardei, 2008), security locations in WSNs (Srinivasan, 2008), secure routing protocols in MANETs (Pervaiz, 2008), challenges and solutions in wireless security (Lou, 2003), key management schemes in WSNs (Xiao, 2007), and open issues in WSNs (Evans, 2006). To increase network security cryptographic techniques may be applied in different areas of MANETs/WSNs. For example, ID-based cryptography (Shamir, 1984) is used to develop a new certificateless security scheme in MANETs as well as for a security scheme in vehicular ad hoc networks and for other secure routing applications. Case studies of cryptographic techniques in customized MANETs and WSNs will provide the research community with the latest updates in security and performance for MANETs and WSNs. One example of a new foundation for advanced research is a configurable library for elliptic curve cryptography in WSNs called TinyECC (Liu, 2008). Our survey is an effort to promote the use of cryptographic techniques in the ongoing research to better secure MANETs/WSNs.

Our case studies are chosen to discuss symmetric cryptography, public key infrastructure (PKI), identity-based cryptography, threshold cryptography, and batch verification of signatures. After summarizing cryptographic techniques we give an overview of commonly used security designs followed by sections on symmetric cryptographic techniques. Our discussion of the symmetric techniques is based on a case study of LHAP (Zhu & Xu, 2003). Our discussion of the asymmetric techniques, with a special emphasis on composite design, is based on a case study of IKM (Zhang, Liu, Lou & Fang, 2006). Then we discuss how threshold cryptography is used in different cases for secret sharing to make gains in both security and performance. Finally other cryptographic techniques are discussed on the basis of a case study of IBV by Zhang (Zhang, Lu, Ho & Shen, 2008) followed by our presentation of present open issues and future challenges.

CRYPTOGRAPHY TECHNIQUES OF SECURE MANETS/WSNS DESIGN

Security is the combination of processes, procedures, and systems used to ensure confidentiality, authentication, integrity, availability, access control, and non-repudiation.

- **Confidentiality:** The confidentiality is to ensure that information is accessible only to those authorized users or nodes to have access. Since MANETs/WSNs use an open medium, all nodes within the direct transmission range can usually obtain the data. One way to keep information confidential is to encrypt the data. In WSNs confidentiality is employed to protect information from inadvertent disclosure while communicating between one sensor node and another sensor node or between the sensors and the base station. Compromised nodes are a threat to confidentiality if the cryptographic keys are not encrypted and stored in the node.
- **Authentication:** The goal of authentication is to identify a node or a user and to prevent impersonation. In wired networks and infrastructure-based wireless networks it is possible to implement a central authority at a router, base station, or access point. However, there is no central authority in MANETs/WSNs, and it is much more difficult to authenticate an entity. Confidentiality can be achieved via encryption. Authentication can be achieved by using a message authentication code (MAC) (Menezes, Oorschot & Vanstone, 1996).
- **Integrity:** The goal of integrity is to keep a message from being illegally altered or destroyed during transmission. When the data is sent through the wireless medium, the data may be modified or deleted by malicious attackers. When malicious attackers can resend altered data the action is known as a *replay attack*. Integrity can be achieved through hash functions.

- **Non-repudiation:** The goal of non-repudiation is to prevent a message sender from later denying that it has sent the message. The entity which produces a message signature cannot later deny having sent that message. In public key cryptography, a node, *A*, signs the message using its private key. All other nodes verify the signed message by using *A*'s public key, and *A* cannot deny that its signature is attached to the message.
- **Availability:** The goal of availability is to keep the network service or resources available for legitimate users. It ensures the survivability of the network despite malicious incidents. In a WSN, for example, sensor node capturing and denial of service attacks are common problems. Outages may be mitigated by providing alternate routes in the protocols employed by the WSN.
- **Access control:** The goal of access control is to prevent unauthorized use of network services and system resources. Obviously, access control is tied to authentication attributes. Access control is the most commonly needed service in both network communications and individual computer systems.

Cryptography is very strongly tied to mathematics and the number theory. Therefore, creating a new composite cryptographic design is difficult without sound security analysis based on cryptographic reasoning. One way to reach this goal is to learn from others by reviewing current MANET/WSN security schemes and by understanding how cryptographic techniques combine with MANETs/WSNs to provide a security service with reasonable network performance, scalability, storage, and synchronization. Certainly, a security design can be evaluated using different techniques, but our goal is to provide helpful insight by studying basic cryptographic techniques (as seen in Figure 1) when applied to authentication, trust management, and key management in MANETs/WSNs. Furthermore, we will study several of the commonly-used cryptographic techniques and see how they are employed to deal with different tasks and how to balance the tradeoff between security and performance.

It is a common approach today to use software engineering design patterns to illustrate the design of object-oriented programming. Likewise, cryptographic techniques can be successfully used in different stages of network bootstrap, packet communication, and evaluation factors in the security and performance of MANETs/WSNs. Once these techniques are understood they are easily applied to new designs of these networks.

Overview of cryptographic techniques

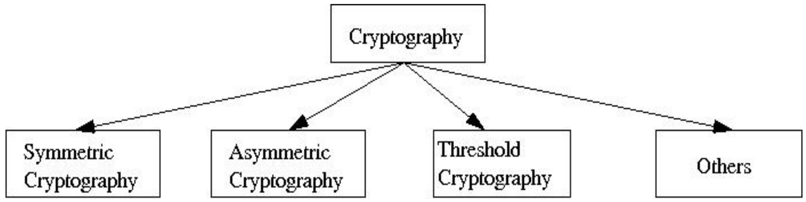
Choosing which and how often specific cryptographic techniques should be used is difficult. Deciding on network performance evaluation metrics and security analysis techniques is also not easy. The first question may be "when does one use symmetric cryptography and when does one use asymmetric cryptography?" For example, in order to get better performance, a hash key chain may be a better choice than an asymmetric private key for encryption due to dynamic topology changes in some MANETs/WSNs. Specifically, alternative temporary symmetric secret keys (e.g., AES with a 128 bit size key) may be better than asymmetric public keys (e,g., RSA with a 1024 bit size public key).

Many researchers have proposed the use of asymmetric cryptography such as public key infrastructure using RSA (Mehuron, 94) or Elliptic Curve Cryptography (ECC) (Salomaa, 1996) to secure wireless ad hoc network routing protocols (Zhou & Haas, 1999; Yi, Naldurg, & Kravets, 2002; Zapata, 2002). But, considering the ad hoc network computation cost to verify asymmetric signatures and the frequency of this verification, symmetric keys for encryption and authentication are proposed (Hu, Perrig, & Johnson, 2002; Zhu & Xu, 2003) to secure routing protocols. One of the commonly-used cryptographic techniques is the one-way hash function, from which other techniques (i.e., hash chain, TESLA key, Merkle hash tree and hash tree chain) are derived. The cryptographic techniques used in some MANET/WSN security research work are shown in Figure 1. (Table 1 gives details of each scheme shown in Figure 1.).

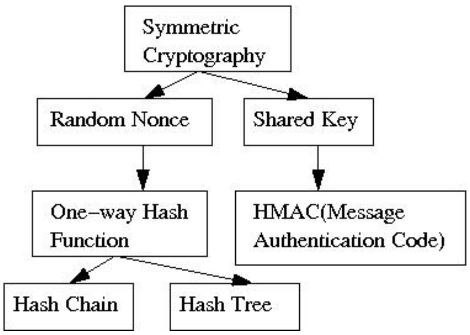
Digital signatures, hash functions, and hash functions based on a message authentication code (HMAC) (Menezes, Oorschot, & Vanstone, 1996) are techniques used for data authentication or integrity purposes in securing MANETs/WSNs. A digital signature is usually signed using a private key and can be verified using a public key. In more detail, a public key is protected by the public-key certificate, in which a trusted entity called the certification authority (CA) in public key infrastructure (Menezes, Oorschot, & Vanstone, 1996) vouches for the binding of the public key with the owner's identity. Those cryptographic techniques are used in most security schemes in MANET/WSN design, for example, SOLSR (Clausen, 2003) and ARAN (Sanzgiri, 2002).

It is very challenging to use different cryptographic techniques to deal with different tasks. The good example is in the countermeasure resource consumption error, where the LHAP scheme shows the art of using composite techniques.

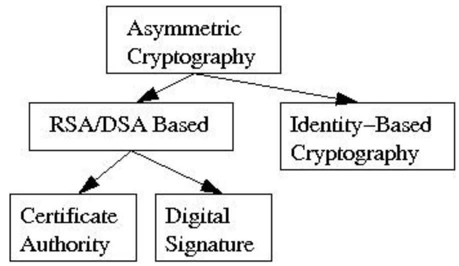
Another popular topic of discussion is to determine how to build up MANETs or WSNs and how to maintain the network. For example, the use of one-way hash chain techniques will determine how to bootstrap the network, how to deliver the key chain, how to let nodes join the network, and how the nodes communicate with neighbors and countermeasure attacks. Other cryptographic techniques have to be considered in the design to establish trust relationships and authentication keys in MANETs in order to complement the use of techniques.



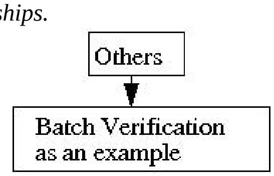
(a) Major components of cryptography applied in MANETs/WSNs.



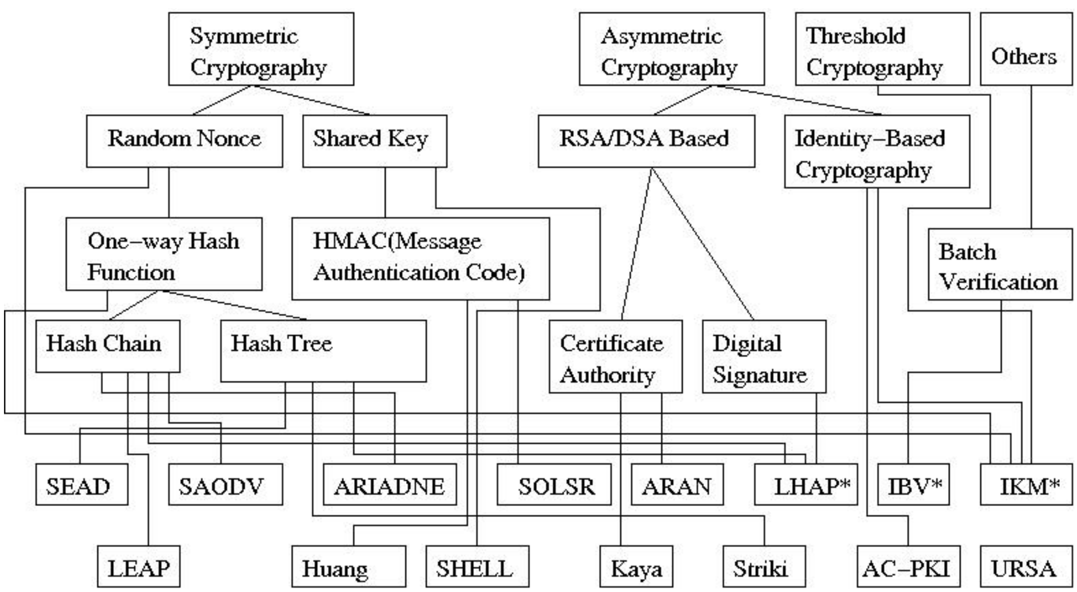
(b) Commonly-used symmetric cryptography techniques and their dependency relationships.



(c) Commonly-used asymmetric cryptography techniques in MANETs/WSNs and their dependency relationships.



(d) Other techniques in MANETs/WSNs.



*(e) Cryptography techniques used in MANETs/WSNs security schemes. Schemes with * are selected as study cases.*

Figure 1: Cryptographic techniques introduction and selected MANET/WSN security schemes applied.

Cryptographic techniques are grouped together and associated with each other to support schemes and protocols in MANET/WSN as shown in Figure 1 (a), (b), (c), (d), (e). Cryptography can be categorized into four parts seen in Figure 1 (a); In detail, symmetric key techniques are shown in Figure 1 (b), in which random nonce, shared keys, one-way hash functions, hash chains, hash trees, and message authentication codes are most-commonly-used in MANET/WSN; and as part of Figure 1(e), those symmetric techniques are used for schemes SEAD (Hu, Johnson, & Perrig, 2002), SAODV (Zapata, 2002), ARIADNE (Hu, Perrig, & Johnson, 2002), SOLSR, LEAP (Zhu, Setia, & Jajodia, 2003), Huang (Huang, Buckingham, & Han, 2005), and SHELL (Younis, Ghumman, & Eltoweissy, 2006). Secondly, asymmetric key techniques are presented in Figure 1 (c), in which public/private keys, RSAs, Digital Signature Algorithms (DSA), ID-based cryptography, certificate servers, and digital signatures are commonly-used techniques in MANET/WSN; and as part of Figure 1 (e), those asymmetric techniques are associated to support schemes such as Kaya (Kaya, 2003), ARAN, LHAP, IKM, AC-PKI (Zhang, Liu, Lou, Fang, & Kwon, 2005), and Striki (Striki & Baras, 2004). Third, threshold cryptography is shown in Figure 1 (e) to support part of the IKM scheme, URSA (Luo & Lu, 2004). Last but not least, batch verification based on ID-based signature is shown in Figure 1(d) to represent other cryptographic techniques that are not included in our survey. For example, the IBV scheme. There are many other cryptographic techniques that can be applied in MANETs/WSNs. In the following paragraphs we show a collection of short reviews of cryptographic techniques and a short discussion of selected MANET/WSN security solutions.

- **Symmetric cryptography:** The encryption key is closely related or identical to the decryption key. In practice, keys represent a shared secret between two or more parties that can be used to maintain private communication.
  Usually the network can choose a shared secret key to encrypt and decrypt the message once two or more parties have used a public/private key pair to build trust in the hand-shaking stages. This is more feasible and efficient from a computational standpoint than asymmetric key techniques.
- **Random nonce:** In the network, a timestamp or random number (nonce) is used to make packets fresh and prevent a replay attack (Kaufman, Perlman, & Speciner, 2002). The session key is often generated from a random number. In the public key infrastructure, the shared secret key can be generated from a random number as well.
  Cryptographic pseudo random generators typically have a large pool of seed values. The design and implementation of cryptographic pseudo random generators can easily become the weakest point of the system.
- **Shared key:** Less computationally intense symmetric key algorithms are used more often than asymmetric algorithms. In practice, asymmetric algorithms are hundreds of times slower than symmetric key algorithms. The most common are AES, RC4 and IDEA. The disadvantage of shared keys in networks is the requirement of $n(n-1)/2$ shared keys among *n* nodes in order to have a secure communication between any two nodes.

  In wireless sensor networks, some protocols use shared keys. Instead of a shared key for each pair of nodes, called pairwise keys, there may be one shared secret key for the entire network, or a group key for each group or cluster of networks. Lee (2007) (Lee, Leung, Wong, Cao, & Chan, 2007) has a detailed discussion using case studies of five key management protocols: Eschnauer

(Eschenauer & Gligor, 2002), Du (Du, 2003), LEAP, SHELL, and Panja (Panja, Madria, & Bhargava, 2006).

- **HMAC message authentication code:** This type of message authentication code is calculated using a hash function in combination with a secret key. Usually in MANETs/WSNs, the hash functions chosen are mostly MD5 or SHA-1. It can also be used to ensure that an unencrypted message retains its original content by calculating the message HMAC using a secret key. For example, see SOLSR, Huang (Huang, Buckingham, & Han, 2005).
- **Hash chain:** It is generated by a successive application of a hash function to a string. Lamport (Menezes, Oorschot & Vanstone, 1996) suggested the use of hash chains as a password protection scheme. Due to the one-way property of secure hash functions, it is impossible to reverse the hash function. A hash chain is a method to produce many one-time keys from a single key, and keys are used in the reversed order of generation. For example, SAODV, ARIADNE, and LEAP are three applications in MANETs/WSNs that use one-way key chains.
- **Hash tree:** It was originally invented to support the handling of many Lamport one-time signatures. At the top of a hash tree there is a top hash or master hash. Nodes higher in the tree are the hashes of their respective children. An example can be found in the MANET/WSN security scheme SEAD.
- **Asymmetric cryptography:** In public key or asymmetric cryptography, there is a pair of public/private keys. The private key is known only to the owner, while the public key is shared with others. One of the earliest public-key cryptographic techniques, known as RSA, was developed in the 1970s. Since then, a large number of encryption, digital signature, key management, and other techniques have been developed in public-key cryptography. Examples include the ElGamal cryptograph system, DSA, and elliptic curve cryptography.
- **Certificate Authority:** A certificate authority is an entity that issues digital certificates for use by other parties. CA is the most important role in many public key infrastructure schemes.

  Whether certificate authorities are practical in MANETs/WSNs is a popular topic of debate. But it is wise to take advantage of the CA role if possible even in MANETs/WSNs. Usually network nodes in MANETs trust the CA in the bootstrap stage and can verify the CA's signature. Then, nodes can also verify whether a certain public key does indeed belong to another node, as it is identified in the certificate. For example, ARAN and Kaya (Kaya, 2003) are two applications in MANETs/WSNs that use certificate authority.
- **Digital signature based on RSA/DSA:** The ElGamal signature is based on the difficulty of breaking the discrete log problem. DSA is an updated version of the ElGamal digital signature scheme published in 1994 by FIPS and was chosen as the digital signature standard (DSS) (Mehuron, 94).

  Digital signature, using the RSA/DSA algorithm, is popular for authentication or confirming the message's integrity. A digital signature scheme typically consists of three algorithms: a key generation algorithm, a signing algorithm, and a signature verifying algorithm.

  In MANETs/WSNs the digital signature is more expensive to compute than a hash function, and digital signatures do not scale well in MANETs/WSNs as the number of nodes grows larger. For example, a digital signature is only performed once in bootstrapping a TESLA key chain in the LHAP scheme.

- **Identity-based cryptography:** This is a type of public-key cryptography. The first identity-based cryptography, developed by Adi Shamir in 1984, uses the identity of the user as a public key. Modern schemes include Boneh/Franklin's pairing-based encryption scheme (Boneh & Franklin, 2001). For example, IKM and AC-PKI schemes are applications that use ID-based cryptography.
- **Batch verification with ID-based signature:** Although there are advantages to ID-based cryptography signature schemes based on pairing, the signature verifications are at least ten times slower than that of DSA or RSA. The batch verification (Yoon, Cheon, & Kim, 2004) of many signatures increases efficiency.

Table 1 lists some security schemes with their security objectives and associated cryptographic techniques.

*Table 1: Overview of cryptographic techniques used in security schemes in MANETs/WSNs. (Schemes without a specific name are specified here according to the author's last name, marked with *.)*

MANET/WSN Security Scheme	**Security Objectives**	**Cryptographic Techniques**
ARAN	Authentication, integrity, and non-repudiation of signaling packets, based on AODV (Perkins, 2001), designed to substitute reactive routing protocols.	Certificate authority, timestamp.
ARIADNE	Authentication and integrity of signal packets, based on the basic operations of DSR (Perkins, 2001).	Symmetric cryptography primitives, hash function and timestamp.
SAODV	Authentication and integrity of signaling packets, a security extension for AODV.	Digital signature and hash chain.
SEAD	Authentication and integrity of signaling packets, based on DSDV (Perkins, 2001), applied to other distance vector protocols.	Hash chain and sequence number.
Huang*	A secure level key infrastructure for multicast to protect data confidentiality via hop-by-hop reencryption and mitigate DoS-based flooding attacks through an intrusion detection and deletion mechanism. The multicast protocol divides a group routing tree into levels and branches in a clustered manner.	MACs and one way sequence number, cluster-based tree as key management.
Kaya*	A dynamic multicast group management protocol is proposed which aims to equally distribute the workload of securing communication to all participating members through MANETs.	Certificate authority and ad hoc group shared key.
LEAP	Source and message one way key chain based authentication and cluster-based shared key in key management to countermeasure wormhole, sinkhole, Sybil, DoS, replay, insider attacks.	Hash chain and cluster-based shared key.
SLSP (Papadimitratos & Haas, 2003)	Authentication, integrity, and non-repudiation of signal packets, extends an intrazone protocol for ZRP (Perkins, 2001).	Certificate authority.

SPAAR (Carter & Yasinsac, 2002)	Authentication, integrity, non-repudiation, and confidentiality, secure position aided ad hoc routing protocol.	Certificate authority and timestamp.
SOLSR	Authentication and integrity of signaling packets.	MACs and timestamp.
SHELL	A cluster-based key management scheme. Each cluster has its own distributed key management entity residing in a-cluster-head node. Therefore, the operational responsibility and key management responsibility are separated, offering better resiliency against node capture.	Group shared key.
LHAP	A hop-by-hop authentication protocol for ad hoc networks.	Digital signature and hash chain.
IKM	Key management to secure mobile ad hoc network, efficient network-wide key update via a single broadcast message.	ID-based cryptography and threshold cryptography.
Striki*	User authentication and Merkle tree-based data authentication in MANETs.	Hash function and hash tree.
IBV	An efficient batch signature verification scheme for vehicular sensor networks.	Batch verification of ID-based signature.

In general, most surveys have been done on security routing and other specific areas such as key management. Our approach differs in that we concentrate on the cryptography techniques used. We prefer to choose cases that include the latest research in an area, putting different cryptographic techniques under review. The following discussion will focus on cryptographic techniques. Using Figure 1 as the outline, we will go through the discussion from symmetric key techniques to asymmetric key techniques, and from RSA/DSA-based schemes to ID-based cryptography, with some discussion about threshold cryptography. Most of the discussion focuses on three cases in MANET/WSN security research: the LHAP scheme, the IKM scheme, and the IBV scheme.

Symmetric key techniques applied in MANETs/WSNs

As seen in Figure 1, symmetric key techniques are used in most security MANETs/WSNs schemes. The techniques are random nonce, shared key, one way hash function, message authentication code, hash chain, and hash tree, as seen in Figure 1 (b). These are used so frequently that we must consider the applicable network factors before the techniques are used in a new design.

One way hash chain and TESLA key (Perrig, Canetti, Tygar, & Song, 2000) are faster than the traditional PKI private key calculation. They are used in the design of several security protocols including SAODV, ARIADNE, and LHAP as shown in Figure 1 (e). One-way hash chains are very easy to compute compared to public key distribution, which typically requires central authentication. Thus, in order to achieve the best performance in the network field, we sometimes use hash functions instead of PKI public keys.

Lamport used one-way hash chains for password authentication. In this instance, a one-way hash chain repeatedly applies a one-way hash function starting from a random number. The user picks up the secret key, which is usually a random number. Supposing that the chain length is N, the user runs the hash function N times on the random number. Actually, each hash function value is a key on the chain. In the list of keys the original random number is the most important key because all other secret keys can be calculated via hash function from this number. If a node wants to generate a key chain of size N, it first needs to choose a key, denoted as *seedKey*, which will be the last one used to do the encryption. The one-way hash chains are generated as follows: $K(0) = seedKey, K(1) = h(K(0),..., K(N)) = h(K(N-1))$, in which h is the one-way hash function. It is infeasible to compute inversely from a one-way hash function. In various standards and applications, the two most-commonly used hash functions are MD5 and SHA-1.

Two commonly-used cryptographic techniques that are used in WSN broadcast authentication are *μTESLA* (Perrig, Szewczyk, Wen, Culler, & Tygar, 2001) and digital signatures. *μTESLA* is considered to be a symmetric cryptography technique, and its variations implement broadcast authentication through delayed disclosure of authentication keys. *μTESLA* keys are based on a symmetric cryptographic hash function, and the operations cost is more efficient even though the network has to be loosely time synchronized and suffers from authentication delays. If digital signatures, such as ECDSA (IEEE, 2006), are used directly for broadcast authentication, they are easily attacked by broadcasting forged packets. The receiving nodes are forced to perform a large amount of unnecessary signature verifications.

To countermeasure DoS attacks when digital signatures are directly used for broadcast authentication, hop-by-hop pre-authentication filters can be used to remove bogus messages before verifying the actual digital signatures. In particular, two filtering techniques, a group-based filter and a key chain-based filter (Dong, Liu, & Ning, 2008), are based on a symmetric cryptographic hash function, hash chain, shared pairwise key, and MAC. When a sender and its neighbor nodes hold a group key in common, an adversary cannot forge messages without compromising the group key. However, a compromised sensor leaks the group key. Alternatively, a sensor node can add a MAC to a broadcast message for each of its neighbor nodes. However, this incurs large communication overhead. Based on the above two simple methods to filter out forged messages, the group-based filter technique has to trade-off communication efficiency with security. Specifically, the group-based filter organizes the neighbor nodes of a sender into multiple groups, which are protected by different keys in a tree structure. In the second filter technique, the key chain-based filter is designed to apply a two-layer filter to deal with the DoS attacks on the verification of signatures and chained keys. On the other hand, one-way key chains feature a simple pre-authentication filter, used by LHAP, which cannot countermeasure the DoS attack because an adversary may claim a key close to the end of the key chain and cause a large amount of unnecessary hash operations. In the two-layer filter the first layer employs a one-way key chain to filter out fake signatures, and the second layer uses existing pairwise keys to prevent a node from conducting unnecessary hash operations.

Key management is a challenging issue in WSNs due to the sensor node's resource constraints. Various key management schemes in WSNs are still based on symmetric key techniques. With varying degrees of key sharing, the key distribution scheme models are generally network keying, pairwise keying, and group keying. For example, in Lee (Lee, Leung, Wong, Cao, & Chan, 2007) the security and operational requirements of WSNs are examined, and five key management protocols - Eschenauer, Du, LEAP, SHELL, and Panja- are reviewed. The key sharing models for WSNs are used to compare the different relationships between the security and operation requirements for WSNs: accessibility, flexibility, and scalability.

Like security, key management in WSNs is comprised of a cross-layered design, which can go from the link layer to the application layer. As an applicable link layer standard in a WSN, IEEE 802.15.4 considers key usage for secure data transmission, but it does not specify how to securely exchange keys. This opens the door to the key management problem that has been the focus of recent research. We sum up the benefits and problems for three models - network keying, pairwise keying and group keying. In network keying the entire network shares a single secret key. The benefits are simple to implement and allow data aggregation and fusion, ease of scale, self-organization, flexibility and accessible. However, compromising one node compromises the entire network, losing robustness. In pairwise keying a pairwise model is chosen to allow each specific pair of nodes to share a different key. Hence, the pairwise model has benefits of best robustness and each node is authenticated, but the pairwise model suffers from scalability problems in storage, energy and computation. In addition, the pairwise model is unable to self-organize and is not flexible for addition or removal of nodes. Last but not least, the group model is designed to let each group use a different shared key. It has benefits of allowing multicast and group collaboration, better robustness than network-wide keying, and adjustable scalability with the ability to self-organize within the cluster. On the other hand, the group model lacks efficient storage methods for group keying to the standard of *IEEE 802.15.4*, and is difficult to securely set up. Also, cluster formation information is application-dependent.

So far, we have discussed one-way hash chains, *μTESLA* key, pre-authentication filters on broadcast authentication in MANETs/WSNs, and shared key models in WSNs. Indeed, using symmetric cryptography in networks is a state-of-the-art advancement. Next, we use the case study of the LHAP protocol to enhance the discussion of symmetric cryptography.

Case study 1: LHAP protocol

In Figure 1, the three cryptographic techniques that are used in the LHAP protocol are shown as hash chain, hash tree, and digital signature. Taking LHAP as our first case study, we show the advantage of using symmetric cryptographic techniques to handle special network situations in security.

One mechanism employs authentication and ensures that only authorized nodes can inject traffic into MANETs to countermeasure resource consumption attacks. As a hop-by-hop authentication protocol for MANETs, LHAP resides between the network layer and the data link layer providing a layer of protection that can counter many attacks, including outsider attacks and insider impersonation attacks.

Many security schemes take advantage of the benefits of hash chains. To illustrate, in Table 2, we present the one way hash chain techniques used in different MANET schemes. To trade reduced security for enhanced performance, various cryptographic techniques are customized for different network services in the LHAP scheme, as illustrated in Table 3.

Table 2: One way hash chain techniques in a variety of MANETs schemes

Secure Routing Protocol	Cryptography Techniques	Network Service Provided
SEAD	One way hash chain	Used on a hop-by-hop basis due to the basic operation of DSV.
ARIANDE	TESLA key	Applied to secure on-demand routing protocols in source-to-destination nature.
LHAP	One way hash chain	Used for traffic packet authentication.
	Merkle hash tree chain	Used to achieve fast hash verification.

Table 3: LHAP scheme cryptographic techniques customized for different network service

LHAP Cryptographic Techniques	Network Rationale
1024-bit RSA digital signature	The most expensive operation in LHAP, but it is only performed once in bootstrapping a TESLA key chain. Therefore the cost is negligible when amortized over the entire packet.
TESLA key	Used to reduce the number of public key operations for maintaining trust between nodes.
One way hash chain (It is more efficient than HMAC over the message.)	Used to authenticate traffic packets for mainly two reasons: 1: One hash time cost is small compared to the overall end-to-end transmission latency of a packet. 2: Limit network memory used for buffering the received packets, and only authenticate traffic packets to its immediate neighbors to prevent an attacker from launching replay attacks.
Merkle hash tree	Used to support fast hash verification; the maximum number of verifications a receiver has to perform is $O(\log(N))$, where N is the length of a TESLA key chain. The verification process only works for TESLA key chains.

In order to counter a resource consumption attack the LHAP protocol is designed to use authentication of traffic packets to avoid bogus packets. Based on wireless ad hoc network analysis, in cases such as network deployment, nodes joining the network, and a node gaining trust from other nodes in the network, trust management may be based on one way hash traffic key chains and a TESLA key chain. To minimize overhead the node uses an RSA digital signature only for gaining trust while using traffic packet authentication in which keys are generated from the one-way hash chain function. Also, to support fast hash verification, LHAP uses a tree-based authentication scheme, namely the Merkle hash tree.

Through this short case study of LHAP, we have shown that symmetric cryptography can be used creatively in special cases, and that it can be used to compare similar networking schemes. Therefore, cryptography technique studies really do help us to organize security design schemes better.

Asymmetric cryptographic techniques applied in MANET/WSN security

From Figure 1, we show that asymmetric cryptography is popularly used in the security of MANET/WSN schemes, detail seen in Figure 1 (e). Most public key infrastructure schemes are either based on RSA/DSA or ID-based cryptography, seen in Figure 1 (c). For example, the most popular scheme, ARAN, has been discussed in many surveys (Lou, 2003; Wu, Cardei, & Wu, 2008; Xiao, 2007).

Public key infrastructure in MANETs is a very popular choice securing the networks. Some schemes (Luo & Lu, 2004; Yi, Naldurg, & Kravets, 2002) use a public-key infrastructure to associate public keys with the node's identity. One of PKI's approaches is to pre-load each node with all other nodes's public key certificates prior to network deployment. This approach has two problems: scalability with network size and public key update if needed. Another approach is to use on-demand certificate retrieval, which is not an optimal choice considering communication latency and overhead. Secure routing protocols, such as ARAN, ARIADNE, SEAD, and SPINS (Perrig, Szewczyk, Wen, Culler, & Tygar, 2001), all are based on the assumption that there is pre-existence and pre-sharing of secret and/or public keys for all the nodes in the network. This leaves ad hoc key management and key distribution as an open problem that must be solved.

Several IBC-based certificate-less public-key management schemes for MANETs have been developed by (1) deploying identity-based cryptography (IBC) and threshold secret sharing and (2) by eliminating the assumption of a pre-fixed trust relationship between nodes,. These include Deng, Mukherjee, & Agrawal, 2004; Khalili, Katz, & Arbaugh, 2003; Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou & Fang, 2006; and Zhang, Liu, Lou, Fang, & Kwon, 2005. The basic idea is to let some or all network nodes share a network master-key. Some of them (Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou, Fang, & Kwon, 2005) use threshold cryptography and collaboratively issue ID-based private keys. The PKI digital signature scheme is widely recognized as the most effective approach for Vehicular Sensor Networks (VSNs) to achieve authentication, integrity, and validity. To avoid scalability problems, the efficient identity-based batch verification scheme (Yoon, Cheon, & Kim, 2004) is proposed, which employs the *batch verification technique* based on IBC (Camenisch, Hohenberger, & Pedersen, 2007). This scheme uses IBC to generate private keys for pseudo identities, so PKI certificates are not needed, and transmission overhead is significantly reduced.

Introduction to identity-based cryptography

In 1984, Shamir proposed the idea behind identity-based encryption. However, there was no workable method to solve the problem until Boneh (2001) invented a practical scheme based on elliptic curves and a mathematical construct called the Weil Pairing.

A bi-linear map is a special mathematical function that makes identity-based encryption work. A bi-linear map is a pairing that has the property: $Pair(a*X, b*Y) = Pair(b*X, a*Y)$.

For identity-based encryption, the operator "*" is used for multiplication of integers with points on elliptic curves. The products, for example $a*X$, are easy to calculate, but the inverse operations, such as finding parameter a from X and value of $a * X$, are practically impossible. The function is one way and practically non-invertible. The concept is actually the same as one-way hash functions; the bi-linear map can be a Weil Pairing.

The following concrete example will more clearly illustrate the pairing technique.

Let p, q be two large primes and E / F_p indicate an elliptic curve $y^2 = x^3 + ax + b$ over the finite field F_p. G_1 is a *q-order* subgroup of the additive group of points of E / F_p, and G_2 is a *q-order* subgroup of the multiplicative group of the finite field $F_{p^2}^*$. The discrete logarithm problem is required to be hard in both G_1 and G_2, which means that it is computationally infeasible to extract the integer x, given $p, q \in G_1$ such that $q = xp$. For example, a pairing is a map $\psi : G_1 \times G_1 \to G_2$ with the following properties:

- Bilinear property:

For $\forall P, Q, R, S \in G_1$, $\psi(\mathrm{P}+\mathrm{Q}, \mathrm{R}+\mathrm{S}) = \psi(\mathrm{P},\mathrm{R})\psi(\mathrm{P},\mathrm{S})\psi(\mathrm{Q},\mathrm{R})\psi(\mathrm{Q},\mathrm{S})$. And also, for $\forall a, b \in Z_q^* = \{a | 1 \le a \le q-1\}$, there is $\psi(aP, bQ) = \psi(aP, Q)^b = \psi(P, bQ)^a = \psi(P, Q)^{ab}$, etc.

- Non-degenerate property: If P is a generator of G_1, then $\psi(P, P) \in F_{p^2}^*$ is a generator of G_2.
- Computable property: There is an efficient algorithm to compute $\psi(P, Q)$ for all $P, Q \in G_1$.

A more comprehensive description of how these pairing techniques work can be found in papers (Barreto, Kim, Bynn, & Scott, 2002; Boneh & Franklin, 2001; Boneh, Franklin, 2003).

In our case study, we choose a hybrid cryptography scheme combining threshold cryptography with ID-based cryptography as a certificateless key scheme IKM.

Case study 2: ID-based key management scheme – IKM

As seen in Figure 1(e), several cryptographic techniques (including random nonce, one way hash function, threshold cryptography and ID-based cryptography) are used in the IKM scheme. Fig 2 uses cryptographic techniques to break down network initialization in the IKM scheme presenting the design in a comprehensive tree-structure. The complicated design of the network initialization is based on a prototype of the most commonly-used case: one random nonce, one node specific identity, and one hash function to apply node's identity. The IKM scheme may be extended with two random nonce, two sets of identities, two hash functions, and many (up to maximum M) phases. Consider this approach a trial use of the most recent scheme in IBC, through which we encourage readers to employ the "cryptographic techniques used" exercise; ask a series of questions regarding how many cryptographic techniques are used, when to use them, and why to use them. This break-down approach is also a training exercise to encourage us to design a security scheme using the cryptographic techniques used in practical approaches in MANETs/WSNs.

After comparing several IBC-based certificate-less public-key management schemes (Deng, Mukherjee, & Agrawal, 2004; Khalili, Katz, & Arbaugh, 2003; Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou, Fang, & Kwon, 2005), IKM solved several issues related to the previous IBC-based key management scheme:

- The security of the whole network is compromised when a threshold number of network nodes who share the network's master key are compromised.
- Significant communication overhead in a large-scale MANET occurs while updating ID-based public/private keys because each node has to contact a threshold number of nodes who share the network master key one by one.
- There is no quantitative argument to prove the advantage of IBC-based public key management schemes over certificate-based cryptography.

One contribution of IKM is to provide a novel construction method of ID-based public/private keys. In IKM each node's public key and private key includes two parts: one is a node specific ID-based element, and the other is a network-wide common element. The node specific ID-based elements are designed to ensure that the compromise of an arbitrary number of nodes does not affect the secrecy of the non-compromised nodes' private keys. With network-wide common key elements a single broadcast message can update the network-wide public/private keys.

Each IKM node has an authentic ID-based public/private key pair and uses the key pair as proof of its group membership. Those key pairs help to implement the mutual authentication, key management, public-key encryption, and digital signatures. The IKM key management scheme consists of three phases: key pre-distribution, revocation, and update.

In the key pre-distribution phase a Private Key Generator (PKG), acting as a trusted authority, prepares a set of system parameters and pre-loads every node with certain key contents during network initialization. Next, the PKG distributes its functionality to *n* distributed authorities which are selected from the overall number of nodes N to enable secure key revocation and update during network operation. The *n* distributed authorities in IKM are called D-PKGs for convenience.

If a node is compromised, its public key may be explicitly revoked. During network operation, if a node suspects that a peer, say A, has been compromised, the node can send a signed accusation against A to some D-PKGs. When the number of accusations against node A reaches a predefined revocation threshold, denoted by γ, in a certain window, the node A is diagnosed as compromised. The D-PKGs can jointly issue a key revocation against A.

As a common practice, public/private keys of mobile nodes are updated at intervals for various reasons, such as preventing cryptanalysis. IKM also takes this approach and the non-revoked node can update its public key autonomously and its private key via a single broadcast message.

IKM is designed to make the distributed authorities D-PKG's indistinguishable from common nodes via anonymous routing (Zhang, Liu, Lou, Fang, & Kwon, 2005). Because of the shared wireless medium, D-PKGs IDs leak in routing and data packets, making D-PKGs vulnerable to pinpoint attacks.

We will now focus on the basics of IKM related to network initialization, key revocation, key update, and its security analysis. We will also discuss threshold cryptography and how the IKM scheme can benefit from previous threshold cryptography analysis.

Network Initialization

In Table 5, the cryptography techniques used in the IKM scheme are reviewed and matched with the detailed IKM scheme functionality. In Figure 2, IKM scheme network initialization, the main ideas are (1) using threshold cryptography to update the network key for each network phase based on a hash function, and (2) node specific public/private key based on ID-based cryptography.

Table 5. The cryptography techniques and their functionalities in IKM scheme

Cryptography techniques	**Design consideration – IKM scheme functionality.**
Random nonce	Used as network master secret keys K_{p_1}, K_{p_2}, in which one constructs a node private key, another constructs a series of network phase private keys.
Hash function	One hash function is used to make a series of network phases. In detail, $salt_i = h(salt_{i-1} + 1)(1 < i \le M)$, *h* is a hash function, such as SHA-1.
	Hash function is chosen for ID-based identity application, H_1, which maps arbitrary string to non-zero element in the subgroup G_1.
ID-based cryptography	Node specific element is related to nodes which can join network anytime, and its major concern is to define its public key and private key. For example, node A with identity ID_A has the keys: $< \Gamma_A, \Gamma_A^{-1} >= (H_1(ID_A), K_{p_1} H_1(ID_A))$.
	Network phase specific element is related to phases in different time period, and its public/private key pair is $(H_1(salt_i), K_{p_2} H_1(salt_i))$.
Threshold cryptography	It is used to apply relatively frequent key update to enhance the security. The IKM is composed of a number of continuous, non-overlapping *key update phases*, denoted by p_i for $(1 < i \le M)$, where *M* is the maximum possible phase index.

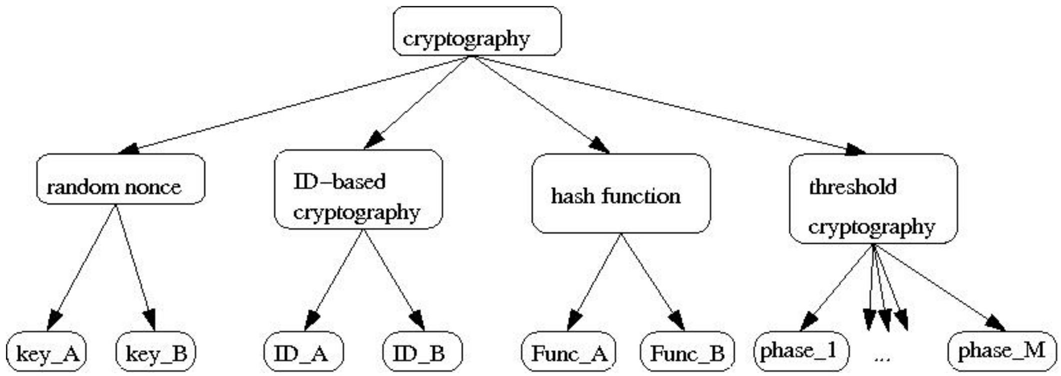


Figure 2: IKM scheme design network initialization demystified – A threshold cryptography and identity-based cryptography composite design tree structure illustration of parameters. Key_A is network master key for all nodes in network. Key_B is network master key for all network phases. ID_A is node specific identity. ID_B is network phase identity. Func_A is a hash function applied in node's identity in network. Func_B is a hash function applied in phases to generate salts. Phase_1 is network phase salt in first phase in the process of relatively frequent key update. Phase_M is network phase salt in Mth phase which is maximum phase index.

The PKG does the following three steps to bootstrap the network. First, generate the pairing parameters (p, q, ψ), and select an arbitrary generator *W* of G_1. Secondly, choose a hash function H_1 that maps arbitrary binary strings to nonzero elements in G_1. Thirdly, choose two distinct random number $K_{p_1}, K_{p_2} \in Z_q^*$ as network master-secrets, and set $W_{p_1} = K_{p_1} W$ and $W_{p_2} = K_{p_2} W$ respectively.

Then, preload parameters $(p, q, \psi, H_1, W, W_{p_1}, W_{p_2})$ to each node; those parameters are public, while network master keys K_{p_1}, K_{p_2} should never be disclosed to any node.

In IKM secret sharing design, only knowledge of K_{p_2} is introduced into the network, and the PKG performs a *(t, n)-threshold* secret sharing of K_{p_2} to avoid the single point of compromise and failure. The random polynomial of threshold cryptograph is $g(x) = K_{p_2} + \sum_{i=1}^{t-1} g_i x^i \pmod q$. Distributed authorities D-PKGs are randomly selected from a subset of size *n* of nodes $(t \le n < N)$. After that the PKG assigns to each node in D-PKG a secret share computed as $K_{p_2}^V = g(ID_v)$. The design is based on the Lagrange interpolation. The PKG's master secret key K_{p_2} can be obtained from value $g(0)$. However, any subset with size $(t-1)$ or smaller cannot reconstruct $g(0)$. The PKG also calculates a set of values to enable verifiable secret sharing. The values $\{W_{p_2}^V = K_{p_2}^V W | V \in \Omega\}$ in which Ω is the D-PKG set are preloaded to each D-PKG. Due to the difficulty of solving the DLP in G_1, none of the other D-PKGs can know the secret share $K_{p_2}^V$ of D-PGK *V* from $W_{p_2}^V$. To make key revocation and update feasible, the IDs of all the D-PKGs are public to each node.

IKM is designed to construct ID-based public/private keys for each node *A*. The IKM contains a number of continuous, non-overlapping key update phases, in which the i^{th} key update period is denoted by p_i for $(1 < i \le M)$, where M is the maximum possible phase index. Each phase p_i is associated with a unique binary string called a phase salt, denoted by $salt_i$. The PKG issues a random number $salt_1$ to each node before the deployment of the network, and with a hash function *h* such as SHA-1, a series of $salt_i$ is generated using $salt_i = h(salt_{i-1} + 1)(1 < i \le M)$.

There are both node-specific and phase-specific public/private key pairs, and node *A*'s key pair is valid only during phase p_i which is denoted by $< \Gamma_{A,p_i}, \Gamma^{-1}_{A,p_i} >$. Each public key Γ_{A,p_i} and private key Γ^{-1}_{A,p_i} is comprised of a node-specific element and a phase specific element common to all the nodes, both in G_1.
$\Gamma_{A,p_i} := (\Gamma_A, \Gamma_{p_i}) = (H_1(ID_A), H_1(salt_i))$, $\Gamma^{-1}_{A,p_i} := (\Gamma^{-1}_A, \Gamma^{-1}_{p_i}) = (K_{p_1} H_1(ID_A), K_{p_2} H_1(salt_i))$.

At the beginning, the PKG issues $< \Gamma_{A,p_1}, \Gamma^{-1}_{A,p_1} >$ to node A from which $< \Gamma_{A,p_i}, \Gamma^{-1}_{A,p_i} > (1 < i \le M)$ is originated from the D-PKGs during network operation. $< \Gamma_{p_i}, \Gamma^{-1}_{p_i} >$ is a common public-key and private-key element of phase p_i, and $< \Gamma_A, \Gamma^{-1}_A >$ is a node-specific public-key and private-key elements of node A. The phase p_i public/private key pair changes across key-update phases, while node A public/private key pairs remain the same during the network lifetime and should not be released to node A itself.

Because it is difficult to solve the discrete logarithm problem in the subgroup G_1, it is not possible to calculate the network master secret K_{p_1} and K_{p_2} from an arbitrary number of public/private key pairs. Therefore, IKM has a property which allows it to keep the confidentiality of the node's private key if the node is compromised, regardless of how many key pairs the adversary is able to acquire from compromised nodes. The IKM scheme has more resilience to the compromization of D-PKGs than the conventional key construction method (Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou, Fang, & Kwon, 2005).

The IKM scheme allows dynamic node joins at any time. Suppose a new node X joins the network at phase p_i, the PKG only needs to pre-equip X with public system parameters and $< \Gamma_{A,p_i}, \Gamma^{-1}_{A,p_i} >$. Based on the support of a node joining the network at any time, the IKM scheme network size grows without limitation, therefore high network scalability is achieved.

Key Revocation

The IKM scheme includes a key revocation design which has three subprocesses: misbehavior notification, revocation generation, and revocation verification. For our case study, we only show the misbehavior notification; for the other two parts refer to the original paper (Zhang, Liu, Lou & Fang, 2006).

Suppose node *B* detects node A's misbehavior. Node B generates a signed accusation $[ID_A, s_B]_{\Gamma^{-1}_{B,p_i}}$ against A, where s_B is a timestamp to countermeasure message replay attacks. If node B sends the revocation message to the D-PKGs, several things must be considered. Since node A may temporarily behave normally, it is not wise for node *B* to naively flood the accusation. Node A may attempt to lower the number of accusations against it down to the level that is below the predefined revocation threshold γ. Therefore, the IKM scheme takes the approach to let node B unicast the accusation secretly to one of the D-PKGs instead.

During network initialization, the PKG provides each node with a function η that maps each node ID to the IDs of β distinct D-PKGs. Any node A in the network node set, denoted by Λ, is assoiciated with the set $\eta(ID_A) = \{ID_{X_j} \mid 1 \le j \le \beta, X_j \in \Omega, X_j \ne A\}$. Therefore the node set Λ is divided into n disjoint node sets, each associated with β distributed authorities D-PKGs.

The β determines the tradeoff between resilience to D-PKG compromise and communication overhead. Smaller β leads to a lower related communication overhead, but also to a less resilient network.

Key Update

It is common practice to update keys to countermeasure the cryptanalysis and limit any potential damage from compromised keys. Previous research in MANETs and WSNs provides the related work for updating keys using threshold cryptography, for example, (Zhou & Haas, 1999; Luo & Lu, 2004). In our desire to become expert at application design, it is in our interest to show threshold cryptography applied in different cases and to determine the primary evaluation factors. So in our case study, we show the details of key update in IKM and network analysis.

A new key update phase p_{i+1} starts either because the previous phase p_i times out or because the number of nodes revoked in p_i is not less than the prescribed threshold. In the IKM scheme each node can update its public/private key autonomously. For example, node *B* uses the following formula: public key case, $\Gamma_{B,p_{i+1}} := (H_1(ID_B), H_1(salt_{i+1}))$, where $salt_i = h(salt_{i-1} + 1)(1 < i \le M)$. From the computation overhead standpoint, there are only two hash operations for node *B* to compute when updating its public key; private key case, we have $\Gamma^{-1}_{p_{i+1}} = K_{p_2} H_1(salt_{i+1})$. Private key update needs work from *t* D-PKGs in Ω. In the IKM scheme, the simple way is to assume that $Z \in \Omega$ initiating phase p_{i+1}, but the D-PKGs should take turns balancing their resource usage. *Z* randomly selects $(t-1)$ other non-revoked distributed authorities D-PKGs from Ω and sends a request to each one.

The key update method of the IKM design provides the network's self healing capabilities. For example, there is a scenario in which any non-revoked node can recover $\Gamma^{-1}_{p_j}$ for any phase $p_j (j > i)$ if the node did not receive the key-update broadcast message due to MANET mobility, channel errors, and temporary network partitions.

Security Analysis On Threshold Cryptography Used

IKM provides more security than other MANET security schemes using certificate key management CKM (Yi & Kravets, 2003; Zhou & Haas, 1999;) and previous identity based cryptograph IBC-based schemes (Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou, Fang, Kwon, 2005 (referred to as o-IKM)).

All these approaches are *(t,n)-threshold* schemes, having the same level of security as long as the *t-limited* assumption holds. The difference is in the worst-case scenario. Table 6 shows the detail. The IKM part of threshold scheme is as secure as conventional certificate based key management CKM's, and it outperforms o-IKM in the worst-case scenario.

Table 6: Threshold cryptography worst case comparison: compromised nodes reaches threshold.

(t,n)-threshold scheme distributed CAs are compromised	**CKM**	**IKM**	**o-IKM**
Can adversaries construct a secret key? If yes, what key is it?	Yes CA's private key.	Yes One of PKG master secret key.	Yes Same as IKM.
Can adversaries deduce the private key of any non-compromised node?	No	No	Yes
Is overall system security lost?	No	No	Yes

After the case study, we will now cover a discussion on threshold cryptography (Shamir, 1979; Desmedt & Frankel, 1989) applied in MANETs and WSNs.

Threshold cryptography applied in MANET/WSN security

In Figure 1 threshold cryptography is shown as a technique used by IKM and URSA schemes in MANET/WSN. Actually the cryptography is widely used in a variety of schemes (Capkun, Buttyan, & Hubaux, 2003; Gouda & Jung, 2004; Kong, Zerfos, Luo, Lu & Zhang, 2001; Luo & Lu, 2004; Saxena, Tsudik, & Yi, 2004; Yi & Kravets, 2003; Zhou & Haas, 1999; Zhang, Liu, Lou & Fang, 2006). We will compare those schemes and discuss the most frequently asked questions when threshold cryptography is applied in MANETs/WSNs.

For detailed background knowledge of threshold cryptography, please refer to the paper (Shamir, 1979; Desmedt & Frankel, 1989). Due to limited space, we don't present the threshold cryptography primitives here. There are several features discussed in research literature, namely verifiable secret sharing (Chor, Goldwasser, Micali, & Awerbuch, 1985; Gennaro, Jarecki, Krawczyk, & Rabin, 1996) and periodical updates on the participants' secret sharing, called proactive secret sharing, (Frankel, Gemmell, MacKenzie, & Yung, 1997; Herzberg, Jarecki, Krawczyk, & Yung, 1995). As applied in MANETs and WSNs, some of them require a trusted centralized authority to bootstrap the secret sharing procedure, while others provide joint secret sharing and do not require any trusted authorities.

Zhou & Haas (1999) used certificate based cryptography (CBC) and *(t,n)-threshold* cryptography in MANET. Let N be the total number of nodes and t, n be the two integers of threshold parameters where $t \le n > N$. Prior to network deployment the certificate authority CA's public key is furnished to each node, while each node's private key is divided into *n* shares, each uniquely assigned to one of *n* chosen nodes. Let us denote them as D-CAs. During network operations any *t* D-CAs can work together to perform certificate generation and revocation using their secret share, while less than t D-CAs cannot restore the secret key. Yi and Kravets (Yi & Kravets, 2003) proposed that it is better to select more computationally powerful and more physically secure nodes as D-CAs. Both schemes tolerate the compromise of up to $(t-1)$ D-CAs and the failure of up to $(n-t)$ D-CAs according to *(t,n)-threshold* cryptography.

Another application of threshold cryptography in MANETs is URSA (Kong, Zerfos, Luo, Lu & Zhang, 2001; Luo & Lu, 2004), which is a (t, N) threshold scheme where *N* is the overall number of nodes. URSA provides the network benefit of increased service availability because a certificate can be generated by any *t* nearby nodes or revoked by any *t* nearby nodes. The pitfall of this design is that the compromise of any *t* out of *N* nodes could break the secret key, that is certificate authorities CA's private key, which leads to loss of overall system security. From the network attacks analysis, several security problems have been studied (Douceur, 2002; Jarecki, Saxena, & Yi, 2004; Narasimha, Tsudik, & Yi, 2003). One major problem is the Sybil (Douceur, 2002) attack, in which an attacker takes as many identities as necessary to collect shares until reaching the threshold after which the CA's private key may be constructed.

Another approach to using threshold cryptography CBC schemes for MANETs is to let each node act as a CA to issue certificates to other nodes (Capkun, Buttyan, & Hubaux, 2003; Gouda & Jung, 2004). This approach is less suitable in MANETs, but it is good for authority-free civilian networks. The IBC-based certificate-less public-key management schemes for MANETs (Deng, Mukherjee, & Agrawal, 2004; Khalili, Katz, & Arbaugh, 2003; Saxena, Tsudik, & Yi, 2004; Zhang, Liu, Lou, Fang, & Kwon, 2005) sometimes use threshold cryptography. Table 7 demonstrates selection criteria applied to threshold cryptography in MANET/WSN. Table 8 is an illustration of the main features and advantages of the various schemes. Table 9 is a collection of threshold cryptography questions and answers seen in papers (Jarecki, Saxena, & Yi, 2004; Narasimha, Tsudik, & Yi, 2003; Zhang, Liu, Lou, & Fang, 2006).

Table 7: Threshold cryptography criteria applied in MANET/WSN schemes.

Certificate authority	Quantities of CA	Asymmetric cryptography	Private key
Selective on network node, not any node in network.	Selective on quantities of CA, not one unique CA.	Selective on RSA/DSA based asymmetric cryptography or IBC based one.	Selective on network-wide element's private key, not node specific element.

Table 8: Threshold cryptography usage in MANET.

Scheme information	Main features	Pros/Cons
Zhou & Hass (1999) CBC scheme	Choose *n* nodes to be D-CAs, each secret key to give n shares, threshold is t, $t \le n > N$.	Traditional approach
Yi & Kravets (2003) CBC scheme	Certificate authorities selected based on network factors: physical security, computation power, etc.	**Pros**: Consider network factors, thus smart choice from network viewpoint.
URSA (Kong, Zerfos, Luo, Lu & Zhang, 2001; Luo & Lu, 2004) CBC scheme	Each of *N* nodes is a D-CA, where *N* is the overall number of nodes.	**Pros:** Increase service availability, any *t* nearby nodes can provide service. **Cons**: Overall security is decreased, e.g. the Sybil attack.
Multiple CA (Capkun, Buttyan, & Hubaux, 2003; Gouda & Jung, 2004)	Each node acts as a CA.	**Cons**: Less authority available in network.
ID-GAC (Saxena, Tsudik, & Yi, 2004) IBC based	IBC-based access control scheme.	**Pros**: Apply in MANET service availability same as URSA. **Cons**: Overall security is decreased.
IKM, IBC based scheme	There are two parts of public/private keys which are node-specific keys and network-wide common keys; nonetheless, the threshold cryptography only applies to network-wide common element.	**Pros**: Node-specific key elements ensure the secrecy of noncomprised nodes's private key; common key elements enable efficient key updates via a single broadcast message.

Table 9: Design questions related to threshold cryptography technique applied in MANET/WSN.

Ideas of threshold cryptography	MANET/WSN network advantage/pitfall analysis
1. Threshold cryptography distributes the ability to decryption or signing etc. service, what is the advantage to use threshold cryptography?	MANET/WSN network has better fault tolerance than non-threshold cryptography, better security.
2. Is secret share verifiable?	If not, it cannot be used in a setting where malicious insiders can exist. It requires a trusted third party to initialize the group during bootstrapping.
3. What is a common problem if MANET has one single trusted authority, one certificate authority CA?	One single trusted authority introduces a single point of failure attack, limited scalability.
4. What are some concerns of configuring MANETs using group authority rather than single one?	Although the group authority can be replicated for better availability, the scalability cannot be addressed by replication alone. Furthermore, unpredicted network faults and partitions complicate placement of group authority “replicas” in the network.
5. Is a fixed threshold policy applicable?	Sometimes it is necessary to reduce the threshold t to motivate the group to operate. A large group of nodes leave the network, resulting in a new smaller group size.
6. How is dynamic group size determined if using dynamic threshold cryptography?	MANET and WSN have distributed, asynchronous and decentralized dynamic group setting. Therefore, every member can send a periodic heart-beat message to the trusted authority to maintain the group size.
7. What cryptography library is commonly used in MANETs?	MIRACL (Chor, Goldwasser, Micali, & Awerbuch, 1985), a standard cryptographic library which is used in IKM.

Other cryptographic techniques applied in security of MANET/WSN

Looking up new research results of applied cryptography and applying them to MANET/WSN security is not as far from reality as it once was. Application only requires time and effort to digest the cryptographic techniques, put together the security analysis, and make up an innovative design.

Of the four categories of cryptography seen in Figure 1 (a), “*others*” is the next topic of discussion. A special cryptography technique called batch verification with ID-based signature (Yoon, Cheon, & Kim, 2004), and its application to the emerging area of vehicular delay tolerant networks, is the third case study in this chapter.

Vehicular sensor networks (VSNs) have been envisioned to be useful in many commercial applications and in road safety systems. It is common practice to apply a digital signature scheme as the countermeasure to attacks and resource abuse for VSNs. Consider the fact that a roadside unit cannot handle receiving a large number of signatures within the short interval, according to the dedicated short range communication broadcast protocol (DSRC). A cryptography technique, called the batch signature verification scheme, based on ID-based cryptography (Fiat, 1989), is applied to communication between vehicles and roadside units. A roadside unit verifies multiple received signatures at the same time to reduce the total verification time dramatically. In VSNs the scheme is designed to employ identity-based cryptography to generate private keys for pseudo identities, achieve conditional privacy preservation, and reduce transmission overhead.

There is an abundance of cryptographic techniques that can be applied in the security of MANETs/WSNs. The latest research in cryptography is advancing so quickly that a new scheme applied to MANET/WSN can dramatically change the performance of that network. For example, the following case study will focus on the vehicular sensor network. Improving the batch verification of signatures from linear time to constant time is an algorithm optimization problem in applied cryptography.

Case study 3: an identity-based batch verification scheme IBV

The design of a new security scheme can be very complicated, but for simplicity, we will go through a simple algorithm run time analysis case of the IBV scheme. While the node identity is used in the IKM scheme, pseudo identity is used with network context in the IBV scheme. Multiple batch verification schemes are updated in applied cryptography. Therefore, the IBV scheme is designed to adapt the work from MANETs/WSNs.

The batch verification scheme is designed to handle all the signatures received within a time interval in less time than it would take to verify the same set of signatures independently. There are several batch cryptographic techniques.

Fiat (1989) introduced batch cryptography in 1989, and several other batch schemes (Cha, & Cheon, 2003; Naccache, M'Raihi, Vaudenay, & Raphaeli, 1994; Yoon, Cheon, & Kim, 2004; Zhang, & Kim, 2003; Zhang, Safavi-Naini, & Susilo, 2003) were proposed later. The batch verification scheme (Camenisch, Hohenberger, & Pedersen, 2007) is based on the CL signature scheme and achieves high computational efficiency by not using random oracles. The batch verification scheme operates in constant time rather than linear time. For example, verifying n signatures takes 3 pairing operations instead of $3n$. So, batch verification can be applied to vehicular sensor networks to achieve good scalability.

The Identity-based Batch Verification (IBV) scheme for vehicular traffic related message transmission includes four phases: the key generation and pre-distribution phase, the pseudo identity and private key generation phase, the message signing phase, and the batch verification phase.

Key generation and pre-distribution

There are several assumptions about the network. Each vehicle is equipped with a tamper-proof device, and there is trusted authority (TA) which is designed to check the vehicle's identity, and generate and pre-distribute the private master keys of the vehicles. Before the network deploys, the trusted authority sets up the system parameters for all road side and onboard units.

Let G be a cyclic additive group generated by *P*, and G_T be a cyclic multiplicative group. G and G_T have the same order *q* which is a big prime number. Let $\psi : G_1 \times G_1 \rightarrow G_T$ be a bilinear map.

The trusted authority generates two master keys by randomly choosing $s_1, s_2 \in Z_q^* = \{a | 1 \le a \le q-1\}$, and computes $P_{pub1} = s_1 P$, $P_{pub2} = s_2 P$ as its public keys.

The tamper-proof device of each vehicle is preloaded with the parameters (s_1, s_2). Each road side unit and vehicle are preloaded with the public parameters $\{G, G_T, q, P, P_{pub1}, P_{pub2}\}$.

Each vehicle is assigned a real identity, denoted as $RID \in G$, and a password, denoted as PWD, where RID uniquely identifies the vehicle, and the PWD is used by the tamper-proof device for authentication.

Pseudo Identity Generation

The tamper-proof device is designed to generate random pseudo identities and corresponding private keys based on identity-based cryptography. The tamper-proof device is designed according to the IBV scheme to be composed of three secure modules: one for authentication, another for pseudo identity generation, and a third for private key generation.

The authentication module protects the tamper-proof device even if it is physically held by the adversary. It authenticates a user's right to use the device's service. In the IBV scheme, the RID is the vehicle's unique real identity and the password PWD can be generated in various ways. The PWD is generated by a trusted authority TA as the signature of RID.

The pseudo identity generation module is designed to generate a list of random pseudo identities from the authentication RID. Each pseudo identity ID is composed of ID_1 and ID_2. The formula to generate ID_1 and ID_2 is: $ID_1 = rP$, and $ID_2 = RID \oplus H(rP_{pub1})$ where *r* is a random nonce and *r* is changed each time so that ID_1 and ID_2 are different for each pseudo ID. $\oplus$ is an Exclusive-OR(XOR) operation. *P* and P_{pub1} are the public parameters preloaded by the trusted authority TA. ID_1 and ID_2 are used by the private key generation module.

The private key generation module uses identity based cryptography. There are two private keys corresponding to the two pseudo identity IDs, denoted as SK_1 and SK_2. And $SK_1 = s_1 ID_1$ and $SK_2 = s_2 H(ID_1 \| ID_2)$, in which $\|$ is the message concatenation operation.

A vehicle can go through the tamper-proof device using PWD and RID and get a list of pseudo identities $ID = (ID_1, ID_2)$ and the associated private keys $SK = (SK_1, SK_2)$. Note that the pseudo identities and the private keys can be generated offline by the tamper-proof device.

Message Signing

Vehicles can sign a message and send it to the roadside unit. In the IBV scheme, the message signing phase is designed as follows.

Suppose the traffic message, denoted by M_i, is generated by a vehicle, denoted by V_i. V_i uses the tamper-proof device to obtain a pseudo identity $ID^i = (ID_1^i, ID_2^i)$ and the corresponding private key $SK^i = (SK_1^i, SK_2^i)$. The vehicle V_i can compute the signature σ_i of the message M_i, where $\sigma_i = SK_1^i + h(M_i)SK_2^i$. Subsequently, the vehicle V_i sends the final message $\langle ID^i, M_i, \sigma_i \rangle$ to its neighboring roadside unit. These steps are done once every *100-300ms* according to the current dedicated short range communication broadcast protocol (DSRC).

The signature of the IBV scheme has no need for any signature certificate to be sent along with the message because identity-based cryptography is used. Only a pseudo identity is sent, which has a length of *42* bytes, the sum of the lengths of ID_1^i and ID_2^i. This is much better than the ECDSA signature scheme of *IEEE 609.2* where a 125 byte certificate is contained in the message.

Secondly, the signature of the IBV scheme does not release any real identity information of the vehicle because a pseudo identity is used.

Batch Verification

When a road side unit (RSU) receives a traffic related message from a vehicle in the IBV scheme, the RSU must verify the signature of the message for two reasons: first to ensure the corresponding vehicle doesn't impersonate any other legitimate vehicle, and secondly to prevent the vehicle from disseminating bogus messages. Details of the verification process of the IBV scheme are illustrated in the following single signature verification and batch verification discussion.

Given the system public parameters $\{G, G_T, q, P, P_{pub1}, P_{pub2}\}$ assigned by the trusted authority TA and preloaded on each RSU and vehicle in the network according to the IBV scheme and given the message $\langle ID^i, M_i, \sigma_i \rangle$ sent by the vehicle V_i, then the signature σ_i can be validated by testing if $\Gamma(\sigma_i, P) = \Gamma(ID_1^i, P_{pub1})\Gamma(h(M_i)H(ID_1^i, ID_2^i), P_{pub2})$ as verified below using bi-linear maps bi-linear feature. Therefore, the computation cost for the RSU to verify a single signature is mainly one MapToPoint hash (Boneh, Lynn, & Shacham, 2001), one multiplication, and three pairing operations.

Given *n* distinct messages denoted as $\langle ID^1, M_1, \sigma_1 \rangle$, $\langle ID^2, M_2, \sigma_2 \rangle, \ldots, \langle ID^n, M_n, \sigma_n \rangle$, respectively, which are sent by *n* distinct vehicles denoted as V_1, V_2, …, V_n, all signatures, denoted as $\sigma_1, \sigma_2, \ldots, \sigma_n$ are valid if $\Gamma(\sum_{i=1}^n \sigma_i, P) = \Gamma(\sum_{i=1}^n ID_1^i, P_{pub1})\Gamma(\sum_{i=1}^n h(M_i)HID^i, P_{pub2})$, in which HID^i denotes $H(ID_1^i \| ID_2^i)$. Detailed verification can be found in the IBV scheme paper (Zhang, Lu, Ho & Shen, 2008).

Batch verification in the IBV scheme reduces the verification delay and the computation cost of verifying *n* signatures by the RSU to *n* MapToPoint hash, *n* multiplication, *3n* addition, *n* one-way hash, and *3* pairing operations. Because the computation cost of a pairing operation is much higher than the cost of a MapToPoint hash and a multiplication cost, the verification time for multiple signatures is constant instead of linear with the size of the batch.

Security Analysis

The IBV scheme design is based on ID-based batch verification which can improve efficiency when many signatures must be verified. With the rising interest in pair-based cryptography, much research on identity-based signatures and performance of batch verification of identity-based signatures has been proposed. Here we focus on the IBV scheme security analysis; the basics of the cryptography foundation that supports the IBV scheme. The following three aspects of security analysis will be presented: message authentication, user identity privacy preservation, and traceability by the trusted authority.

- **Message authentication in the IBV scheme:** In review, the IBV signature $\sigma_i = SK_1^i + h(M_i)SK_2^i$ is a one-time identity-based signature. It is impossible to forge an IBV signature without knowing the private key SK_1 and SK_2. The NP-hard computational complexity of the Diffie-Hellman problem in G makes the private key SK_1 and SK_2 derivation from ID_1, P_{pub1}, *P* and $H(ID_1 \| ID_2)$ infeasible. The Diphantine equation is used to construct the IBV signature σ_i, and it is infeasible to compute the private key SK_1 and SK_2 from knowledge of σ_i and $h(M_i)$.
- **Identity privacy preservation:** In the design of the IBV scheme preserving identity privacy is implemented using the ElGamal-type ciphertext construction. The real identity RID of a vehicle is used to construct two random pseudo identities ID_1 and ID_2, where $ID_1 = rP$ and $ID_2 = RID \oplus H(rP_{pub1})$, in which *r* is random number, *P* and P_{pub1} are public parameters that are preloaded on each roadside and vehicle unit. The master-key (s_1, s_2) is preloaded on each vehicle tamper-proof device. Thus, without the master key (s_1, s_2), it is impossible to get the real identity from the pseudo identity pair. Also, because the pseudo identities (ID_1, ID_2) in each signature are distinct, it is not helpful to compound the series of signatures to get the real identity. In other words, there is no linkability.
- **Traceability by the trusted authority:** In the proposed IBV scheme, the trust authority (TA) can authenticate the signature by using the master key (s_1, s_2) which is preloaded to each tamper-proof device on each vehicle. The value of RID can be computed by evaluating $ID_2 \oplus H(s_1 ID_1)$ via the following steps: $ID_2 \oplus H(s_1 ID_1) = RID \oplus H(rP_{pub1}) \oplus H(s_1 rP)$, $P_{pub1} = s_1 P$. From the above two equations, we get $ID_2 \oplus H(s_1 ID_1) = RID \oplus H(rs_1 P) \oplus H(s_1 rP)$, in which $H(rs_1 P) \oplus H(s_1 rP) = 1$. Thus, we conclude that $ID_2 \oplus H(s_1 ID_1) = RID$.

OPEN ISSUES AND FUTURE DIRECTIONS

Further MANET/WSN research in industry and academia will make progress as it emphasizes cryptology, with each new cryptographic technique making its own impact in different case studies as well as in overall network security. Among the numerous possibilities are research in vehicular sensor networks, global positioning systems, and new wireless devices. The more cryptographic techniques available to the designer the greater will be the variations possible in the design. For instance, there are several alternatives to ElGamal type ciphertext which can be used to hide the real identity of a vehicle in the IBV scheme.

Some of the research deals with long term effects. Our current research explores more foundational aspects of security, such as the categorization of cryptographic primitives, security routing protocols, broadcast communication, group key and composite key management, and batch verification. Specifically, this chapter's survey of applied cryptography helps overcome the difficulty of understanding complicated security designs.

Other researchers focus on specific, real life problems. For instance, Wu & Chen (2008) investigate attacks and countermeasures within various network layers. Kannhavong (Kannhavong, Nakayama, Nemoto, & Kato, 2007) survey routing attacks and countermeasures against those attacks in MANETs.

Applying improved cryptographic algorithms to the security of MANETs/WSNs has already reduced the computational costs of cryptographic primitive operations and suggested less expensive dedicated cryptographic hardware for the future. For instance, in the IKM evaluation, the IKM's computation cost as an IBC scheme is shown to be less than RSA operations. And, Zhang (2006) pointed out that the Barreto approach can expedite the Tate pairing to be up to 10 times faster than previous methods, although the implementation is still under way.

Much research has been done related to MANET/WSN location privacy. Such techniques as association rules hiding, statistical combinatorics, and data mining can be helpful in the area of ad hoc network privacy. For example, Aggarwal & Yu (2008), address the privacy model and its algorithms against attacks using background knowledge and patterns.

More research is required in the areas of secure routing and key management in MANETs/WSNs. Key management is always a fundamental issue, and cryptographic techniques always play a major role in the handling of keys.

With multiple wireless networks becoming increasingly more important in our daily business lives, it is much easier both to form a MANET/WSN and to expect to run a greater variety of applications on that network. This great variety of possibilities requires network scalability, computer cost, and resource constraints to be considered on a case by case basis. For example, in vehicular sensor networks, power and processing constraints are less important than with MANETs. In addition, the vehicle has temporary infrastructure access via road-side units as seen in the IBV scheme.

Looking ahead, the use of symmetric cryptography and asymmetric cryptography, and their customized usage according to different network stages, will always be a challenge in covering the wide range of network layers in MANETs/WSNs. The current cryptography libraries will expand, and the number of available MANET simulators, and self-developed simulation studies, will increase. Future MANET/WSN security research will explore various ways to reduce complexity and increase abstraction levels as the field moves forward along with all other innovative technologies.

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REFERENCES

Aggarwal, C., & Yu, P. (2008). Privacy-Preserving Data Mining Models and Algorithms. Springer Science Business Media, LLC.

Barreto, P., Kim, H., Bynn, B., & Scott, M. (2002). Efficient Algorithms for Pairing-Based Cryptosystems. *Proc. CRYPTO* (pp. 354-368).

Boneh, D., & Franklin, M. (2001). Identify-Based Encryption from the Weil Pairing. *Proc. CRYPTO'01* (pp. 213-229).

Boneh, D. & Franklin, M. (2003, March). Identify-Based Encryption from the Weil Pairing. *SIAM J. Computing vol. 32, no. 3* (pp. 586-615).

Boneh, D., Lynn, B., & Shacham, H. (2001). Short signatures from the weil pairing. In *Proceedings of Asiacrypt, Vol.2248* (pp.514-532).

Camenisch, J., Hohenberger, S., & Pedersen, M. (2007). Batch verification of short signatures. In *Proceedings of EUROCRYPT, LNCS, Vol. 4514* (pp. 246-263).

Camenisch, J., & Lysyanskaya, A. (2004). Signature schemes and anonymous credentials from bilinear maps. In *Proceedings of Crypto, LNCS, Vol. 3152* (pp. 56-72).

Capkun, S., Buttyan, L., & Hubaux, J.P. (Jan. - Mar. 2003). Self-Organized Public Key Management for Mobile Ad Hoc Networks. *IEEE Trans. Mobile Computing, vol.2, no.1* (pp.52-64).

Carter, S., & Yasinsac, A. (2002, November). Secure Position Aided Ad hoc Routing Protocol. In *Proceedings of the IASTED International Conference on Communications and Computer Networks (CCN02).*

Cha, J.C., & Cheon, J.H. (2003). An identity-based signature from gap Diffie- Hellman groups. In *Proceedings of Public Key Cryptography* (pp. 18-30).

Chor, B., Goldwasser, S., Micali, S., & Awerbuch, B. (1985). Verifiable secret sharing and achieving simultaneity in the presence of faults. In *FOCS*.

Clausen, T., Adjih, C., Jacquet, P., Laouiti, A., Muhlethaler, A., & Raffo, D. (2003, June). Securing the OLSR Protocol. In *Proceeding of IFIP Med-Hoc-Net*.

Dedicated Short Range Communications (DSRC), [Online]. Available: http://grouper.ieee.org/groups/scc32/dsrc/index.html

Deng, H., Mukherjee, A., & Agrawal, D. (2004, April). Threshold and Identity-Based Key Management and Authentication for Wireless Ad Hoc Networks. *Proc. Int'l Conf. Information Technology: Coding and Computing (ITCC '04).*

Desmedt, Y., & Frankel, Y. (1989, August). Threshold Cryptosystems. *Proc. CRYPTO '89* (pp. 307-315).

Dong, Q., Liu, D., & Ning, P. (2008). Pre-Authentication Filters: Providing DoS Resistance for Signature-Based Broadcast Authentication in Wireless Sensor Networks. In *Proceedings of ACM Conference on Wireless Network Security* (WiSec).

Douceur, J.R. (Mar. 2002). The Sybil Attack. *Proc. First Int'l Workshop Peer-to-Peer Systems (IPTPS '02)* (pp. 251-260).

Du, W., et al. (2003). A Pairwise Key Predistribution Scheme for Wireless Sensor Networks. In *Proc. 10th ACM Conf. Comp. Commun. Sec.* (pp. 42-51).

Eschenauer, L., & Gligor, V.D. (2002). A Key-Management Scheme for Distributed Sensor Networks. In *Proc. 9th ACM Conf. Comp. and Commun. Sec.* (pp. 41-47).

Evans, J., Wang, W., & Ewy, B. (2006). Wireless networking security: open issues in trust, management, interoperation, and measurement. *International Journal of Security and Networks (IJSN), vol.1, no. ½* (pp. 84-94).

Fiat, A. (1989). Batch RSA. In *Proceedings of Crypto* (pp. 175-185).

Frankel, Y., Gemmell, P., MacKenzie, P.D., & Yung, M. (1997). Optimal resilience proactive public-key cryptosystems. In *FOCS*.

Gouda, M.G., & Jung, E. (Mar. 2004). Certificate Dispersal in Ad-Hoc Networks. *Proc. 24th IEEE Int'l Conf. Distributed Computing Systems* (ICDCS '04).

Gennaro, G., Jarecki, S., Krawczyk, H., & Rabin, T. (1996). Robust and efficient sharing of rsa functions. In *CRYPTO*.

Herzberg, A., Jarecki, S., Krawczyk, H., & Yung, M. (1995). Proactive secret sharing, or: How to cope with perpetual leakage. In *CRYPTO*.

Hu, Y., Johnson, D., & Perrig, A. (2002). SEAD: Secure Efficient Distance Vector Routing in Mobile Wireless Ad-Hoc Networks. *Proc. of the 4th IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'02)* (pp. 3-13).

Hu, Y., Perrig, A., & Johnson, D. (2002). Ariadne: A Secure On-Demand Routing for Ad Hoc Networks. *Proc. of MobiCom 2002*, Atlanta.

Huang, J., Buckingham, J., & Han, R. (Sep. 2005). A Level Key Infrastructure for Secure and Efficient Group Communication in Wireless Sensor Networks. In *Proc. 1st Int'l. Conf. on Security and Privacy for Emerging Areas in Commun. Net.* (pp. 249-260).

IEEE Standard 1609.2 - IEEE Trial-Use Standard for Wireless Access in Vehicular Environments - *Security Services for Applications and Management Messages*, 2006.

Ilyas, M. (2003). *The Handbook of Ad Hoc Wireless Networks*. CRC Press.

Jarecki, S., Saxena, N., & Yi, J.H. (Oct. 2004). An Attack on the Proactive RSA Signature Scheme in the URSA Ad Hoc Network Access Control Protocol. *Proc. Second ACM Workshop Security of Ad Hoc and Sensor Networks (SASN '04).*

Kannhavong, B., Nakayama, H., Nemoto, Y., & Kato, N. (October 2007). A Survey of Routing Attacks in Mobile Ad Hoc Networks. In *IEEE Wireless Communications* (pp. 85-91).

Kaufman, C., Perlman, R., & Speciner, M. (2002). *Network Security Private Communication in a Public World*. Prentice Hall PTR, A division of Pearson Education, Inc.

Kaya, T., et al., Secure Multicast Groups on Ad Hoc Networks. (Oct. 2003). In *Proc. ACM SASN '03* (pp. 94-103).

Khalili, A., Katz, J., & Arbaugh, W. (2003, January). Toward Secure Key Distribution in Truly Ad Hoc Networks. *Proc IEEE Workshop Security and Assurance in Ad Hoc Networks***.**

Kong, J., Zerfos, P., Luo, H., Lu, S., & Zhang, L. (Nov. 2001). Providing Robust and Ubiquitous Security Support for Mobile Ad Hoc Networks. *Proc. IEEE Int'l Conf. Network Protocols*.

Lee, J., Leung, V., Wong, K., Cao, J., & Chan, H. (2007, October). Key management issues in wireless sensor networks: current proposals and future developments. In *IEEE Wireless Communications* (pp. 76-84).

Liu, A., & Ning, P. (2008, April). TinyECC: A Configurable Library for Elliptic Curve Cryptography in Wireless Sensor Networks. In *Proceedings of the 7th International Conference on Information Processing in Sensor Networks (IPSN 2008), SPOTS Track* (pp. 245-256).

Lou, W., & Fang, Y. (2003). A Survey of Wireless Security in Mobile Ad Hoc Networks: Challenges and Available Solutions. In X. Chen, X. Huang and D. Du. Kluwer (Ed.), *Ad Hoc Wireless Networks* (pp. 319-364). Academic Publishers.

Luo, H., & Lu, S. (2004). URSA: Ubiquitous and Robust Access Control for Mobile Ad-Hoc

Networks. *IEEE/ACM Transactions on Networking*. *Vol.12 No.6* (pp. 1049-1063).

Mehuron, W. (1994). Digital Signature Standard (DSS). *U.S. Department of Commerce, National Institute of Standards and Technology (NIST), Information Technology Laboratory (ITL)*. FIPS PEB 186.

Menezes, A., Oorschot, P., & Vanstone, S. (1996). *Handbook of Applied Cryptography*. CRC Press.

Naccache, D., M'Raihi, D., Vaudenay, S., & Raphaeli, D. (1994). Can D.S.A be improved? complexity trade-offs with the digital signature standard. In *Proceedings of EUROCRYPT, LNCS, Vol. 950* (pp. 77-85).

Narasimha, M., Tsudik, G., & Yi, J.H. (Nov. 2003). On the Utility of Distributed Cryptography in P2P and Manets: The Case of Membership Control. *Proc. IEEE Int'l Conf. Network Protocols*.

Panja, B., Madria, S. K., & Bhargava, B. (2006). Energy and Communication Efficient Group Key Management Protocol for Hierarchical Sensor Networks, SUTC '06. In *Proc. IEEE Int'l. Conf. Sensor Networks, Ubiquitous, and Trustworthy Comp.* (pp. 384-393).

P. Papadimitratos & Z. J. Haas. (2003, January) Secure Link State Routing for Mobile Ad Hoc Networks. In *Proceedings of the 2003 Symposium on Applications and the Internet Workshops (SAINT'03)* (pp.379-383) Washington, DC, USA.

Perrig, A., Canetti, R., Tygar, J, & Song, D. (2000). The TESLA Broadcast Authentication Protocol. Internet Draft.

Perrig, A., Szewczyk, R., Wen, V., Culler, D., & Tygar, D. (2001, July). SPINS: Security protocols for sensor networks. In *Proceedings of Seventh Annual International Conference on Mobile Computing and Networks* (MobiCom).

Perkins, C. (2001). *Ad Hoc Networks*. Addison-Wesley.

Pervaiz, M.O., Cardei, M., & Wu, J. (2008). Routing Security in Ad Hoc Wireless Networks. In S. Huang, D. MacCallum, and D. -Z. Du (Ed.), *Network Security*. Springer.

Salomaa, A. (1996). *Public-Key Cryptography*. Springer-Verlag.

Sanzgiri, K., Dahill, B., Levine, B., Shields, C., & Belding-Royer, E. (2002). A Secure Routing Protocol for Ad Hoc Networks. *Proc. of IEEE International Conference on Network Protocols (ICNP)* (pp. 78-87).

Srinivasan, A., Wu, J. (2008). A Survey on Secure Localization in Wireless Sensor Networks. In B. Furht (Ed.), *Encyclopedia of Wireless and Mobile Communications*. CRC Press, Taylor and Francis Group.

Saxena, N., Tsudik, G., & Yi, J. (Dec. 2004). Identity-Based Access Control for Ad Hoc Groups. *Proc. Int'l Conf. Information Security and Cryptology*.

Shamir, A. (1979). How to Share a Secret. *Comm. ACM, vol. 22, no. 11* (pp.612-613).

Shamir, A. (1984). Identity Based Cryptosystems and Signature Schemes. *Proc. CRYPTO'84* (pp. 47-53).

Striki, M., & Baras, J. (2004, June). Towards Integrating Key Distribution with Entity Authentication for Efficient, Scalable and Secure Group Communication in MANETs. *In Proc. IEEE ICC'04, vol.7* (pp. 4377-4381).

Wu, B., Cardei, M., & Wu, J. (2008). A Survey of Key Management in Mobile Ad Hoc Networks. In J. Zheng, Y. Zhang, and M. Ma (Ed.), *Handbook of Research on Wireless Security*. Idea Group Inc..

Wu, B., Chen, J., Wu, J., & Cardei, J. (2008). A Survey on Attacks and Countermeasures in Mobile Ad Hoc Networks, In Y. Xiao, X. Shen, and D. -Z. Du (Ed.), *Wireless/Mobile Network Security*. Springer.

Xiao, Y, & Rayi, V. (2007). A survey of key management schemes in wireless sensor networks. *Computer Communications*.

Yi, S., Naldurg, P., & Kravets, R. (2002). *Security Aware Ad hoc Routing for Wireless Networks*. (Tech. Rep. No. UIUCDCS-R-2002-2290). Illinois, United States of America: University of Illinois at Urbana-Champaign.

Yi, S. & Kravets, R. (2003, April). Moca: Mobile Certificate Authority for Wireless Ad Hoc Networks. *Proc. Second Ann. PKI Research Workshop (PKI '03).*

Yoon, H., Cheon, J.H., & Kim, Y. (2004). Batch verification with ID-based signatures. In *Proceedings of Information Security and Cryptology* (pp. 233-248).

Younis, M. F., Ghumman, K., & Eltoweissy, M. (2006). Location-Aware Combinatorial Key Management Scheme for Clustered Sensor Networks. In *IEEE Trans. Parallel and Distrib. Sys., vol.17,* 2006 (pp. 865-882).

M. Zapata. (2002). Secure Ad Hoc On-Demand Distance Vector (SAODV). Internet draft, draft-guerrero-manet-saodv-01.txt.

Zhang, C., Lu, R., Ho, P., & Shen, X. (2008). An Efficient Identity-based Batch Verification Scheme for Vehicular Sensor Networks. *Proc. Of IEEE INFOCOM.*

Zhang, F., & Kim, K. (2003). Efficient ID-based blind signature and proxy signature from bilinear pairings. In *Proceedings of ACISP, LNCS, Vol. 2727* (pp. 312-323).

Zhang, F., Safavi-Naini, R., & Susilo, W. (2003). Efficient verifiably encrypted signature and partially blind signature from bilinear pairings. In *Proceedings of Indocrypt, LNCS, Vol. 2904* (pp. 191-204).

Zhang, Y., Liu, W., Lou, W., Fang, Y., & Kwon, Y. (2005, May). AC-PKI: Anonymous and Certificateless Public-Key Infrastructure for Mobile Ad Hoc Networks. *Proc. IEEE Int'l Conf. Comm* (pp. 3515-3519).

Zhang, Y., Liu, W., Lou, W., & Fang, Y. (2006, Oct.-Dec.). Securing mobile ad hoc networks with certificateless public keys. *IEEE Transactions on Dependable and Secure Computing* (Vol. 3, No. 4, pp 386-399).

Zhang, Y., Liu, W., & Lou, W. (2005, March). Anonymous Communications in Mobile Ad Hoc Networks. *Proc. IEEE INFOCOM '05* (pp. 1940-1951).

Zhou, L., & Haas, Z. (1999). Securing Ad Hoc Networks. *IEEE Network Magazine*, *Vol.13 No.6* (pp. 24-30).

Zhu, S., Xu, S., Setia, S., & Jajodia, S. (2003). LHAP: A Lightweight Hop-by-Hop Authentication Protocol for Ad-Hoc Networks. *23rd International Conference on Distributed Computing Systems Workshops (ICDCSW'03).*

Zhu, S., Setia, S., & Jajodia, S. (2003). LEAP: Efficient Security Mechanisms for Large-Scale Distributed Sensor Networks. In *Proc. 10th ACM Conf. Comp. and Commun. Sec.* (pp. 62-72).

KEY TERMS & DEFINITIONS

Symmetric cryptography: The encryption key is closely related or identical to the decryption key. In practice, keys represent a shared secret between two or more parties that can be used to maintain private communication.

Random nonce: In the network, a timestamp or random number (nonce) is used to make packets fresh and prevent a replay attack. Cryptographic pseudo random generators typically have a large pool of seed values.

Shared key: Less computationally intense symmetric key algorithms are used more often than asymmetric algorithms. In practice, asymmetric algorithms are hundreds of times slower than symmetric key algorithms. The most common are AES, RC4 and IDEA.

HMAC message authentication code: This type of message authentication code is calculated using a hash function in combination with a secret key. Usually in MANETs/WSNs, the hash functions chosen are mostly MD5 or SHA-1. It can also be used to ensure that an unencrypted message retains its original content by calculating the message HMAC using a secret key.

Hash chain: It is generated by a successive application of a hash function to a string. Due to the one-way property of secure hash functions, it is impossible to reverse the hash function. A hash chain is a method to produce many one-time keys from a single key, and keys are used in the reversed order of generation.

Hash tree: It was originally invented to support the handling of many Lamport one-time signatures. At the top of a hash tree there is a top hash or master hash. Nodes higher in the tree are the hashes of their respective children.

Asymmetric cryptography: In public key or asymmetric cryptography, there is a pair of public/private keys. The private key is known only to the owner, while the public key is shared with others. One of the earliest public-key cryptographic techniques, known as RSA, was developed in the 1970s.

Certificate authority: A certificate authority is an entity that issues digital certificates for use by other parties.

Digital signature based on RSA/DSA: The ElGamal signature is based on the difficulty of breaking the discrete log problem. DSA is an updated version of the ElGamal digital signature scheme published in 1994 by FIPS and was chosen as the digital signature standard (DSS).

Digital signature, using the RSA/DSA algorithm, is popular for authentication or confirming the message's integrity. A digital signature scheme typically consists of three algorithms: a key generation algorithm, a signing algorithm, and a signature verifying algorithm.

Identity-based cryptography: This is a type of public-key cryptography. The first identity-based cryptography, developed by Adi Shamir in 1984, uses the identity of the user as a public key. Modern schemes include Boneh/Franklin's pairing-based encryption scheme.

Batch verification with ID-based signature: Although there are advantages to ID-based cryptography signature schemes based on pairing, the signature verifications are at least ten times slower than that of DSA or RSA. The batch verification of many signatures increases efficiency.