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A Secure Key Management Scheme in Wireless Mesh Networks

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***Abstract*—Wireless mesh network (WMN) is a rapid deployed, self organized and multi-hop wireless networks. The wireless and distributed natures of WMNs make them subject to various kinds of attacks, which raise a great challenge in securing these networks. Most existing security mechanisms are based on cryptographic keys where a high degree key management services are in demand. In this paper, we present an effective key management scheme which seeks an encryption key assignment such that the induced network is connected and well protected against potential eavesdropping attacks. Compared with previous work, our scheme assigns the available encryption keys among all the nodes in the network. The simulation results show that our scheme out performs previous schemes through providing a network that is resistant against malicious eavesdropping attack.**

Keywords: Wireless mesh network, secure key management, adversary, malicious eavesdropping attack.

I. Introduction

A wireless mesh network (WMN) is a multihop wireless network consisting of a large number of wireless nodes, such as mesh gateways (*which are connected with a wired network to the internet*), mesh routers (*which can relay packets through wireless channels*), and mesh end users [1][8][9]. The architecture of WMN is shown in Fig. 1. With more attentions on WMNs lately, the security issues become more important and urgent for managing and deploying in such networks [13]. The flexible deployment nature and the lack of fixed infrastructure make WMNs suffer from varieties of security attacks [13], where the existence of such attacks might hold back the potential advantages and wide scale deployment of this promising wireless network technology. Most current security mechanisms (*e.g., encryption and digital signature*) which can be used for WMNs are based on cryptographic keys and thus providing a well designed key management services are in demand [2]. Key management service responsibilities include establishing a trusted secure communication between nodes as well as keep track of bindings between keys [2].

Recent researches have shown that security attacks is holding back the potential advantages and wide-scale deployment of wireless networking technology [13]. Several key management schemes [5][7][13] have been proposed for wireless networks and claimed to have high security. However, their weakness such as high computational overhead, storage overhead and vulnerability to some kinds of attacks are undeniable.

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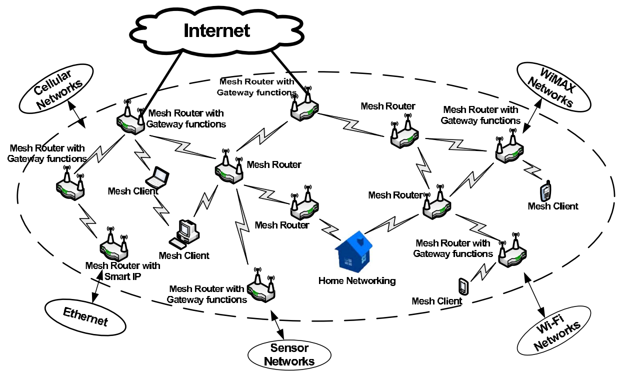


Fig. 1. Wireless mesh network architecture

Du *et al.* in [5] proposed a key management scheme for heterogenous sensor networks. Each high-end sensor is preloaded with M keys, and each low-end sensor is preloaded with L keys ($M >> L$) in a *pre-distribution phase*, where the keys are randomly picked from a pool of keys P without replacement. Followed by the *discovery phase*, which is used to check if neighboring sensors have a shared key, and the *key setup phase*, which is used to find a shared key between any two neighboring sensors when the discovery phase returns that there is no common key between them. *The pool size can affect this proposed scheme*, where with a large pool size and a small K keys randomly selected from P to be stored in each node, a better security can be provided [5]. On the other hand with small pool size, there will be a chance of having more nodes shared common keys in the neighborhood which might harm the network due to various adversary attacks. Moreover, not all the generated keys in the pool are being used nor the keys in high-end or low-end sensors. Our proposed scheme use the available number of keys (K) to be assigned *among* all the nodes, without generating too many unnecessary keys, and keep the network as secure as possible.

Zhao *et al.* in [13] propose an elliptic curve cryptosystem (ECC)-based self-certified public key cryptosystem. Another key management scheme has been proposed in [6], in which the authors designed a key management scheme that includes selective distribution and revocation of keys to sensor nodes as well as node rekeying. In their work, they proposed a scheme that consists of a key pre-distribution phase followed by a shared key discovery phase to establish the topology. Our proposed scheme differ from this scheme where the network topology is known in advance, and we assign K keys among the nodes, in a way to provide a secured pre-established topology. Another study in [4] considers the problem of designing a key management scheme in a clustered distributed sensor networks, where the probability of node compromise in different deployment regions is known in advance. Different probability of node compromise values are assigned to different subgroup. Our proposed scheme differs in that, all nodes in the network have the same probability to be compromised.

The rest of this paper is organized as follows. Our system model and motivations are discussed in Section II. We formally define our problem we are going to study in Section III. Our secure key management scheme is presented in Section IV, which is followed by numerical results in Section V. We conclude the paper in Section VI.

II. Models and Motivations

First in this section, we will describe our network model and the adversary model. Then, formally we will discuss our motivations towards this work. Note that, in this work the terms edge and link are interchangeable, the term mesh router (MR) and mesh node or simply node are interchangeable, also the term encryption key and key are interchangeable.

A. Network Model

We assume a large WMN consists of a number of mesh routers (MR)s which are stationary and without energy constraints. These MRs provide access to mesh clients and also relay information from one MR to another through wireless multi-hop. All MRs use the same fixed transmission power ($R > 0$). We use a undirected bi-connected graph $G(V; E)$ to model the wireless mesh network where V is the set of n nodes and E is the set of m links in the network. For each pair of nodes $(u; v)$, there exist a undirected edge $e \in E$ if and only if $d(u; v) \leq R_u$, where $d(u; v)$ is the Euclidean distance between u and v, and R_u is the transmission range of node u. Each edge between any pair of nodes $(u; v)$ in G corresponds to a potential wireless link between nodes u and v in the network. Note that, in this work for security purposes, we assume that there is no communications between any two neighboring nodes (*nodes in the transmission range of each other*), unless they shared a common encryption key.

B. Threat Model

To disturb WMN operations, the adversary may launch arbitrary attacks such as passive eavesdropping, bogus message injection and physical-layer jamming [10]. In this paper we focus on passive eavesdropping attacks in WMNs. Due to the broadcast nature of wireless channels, all nodes that fall in the transmission range of a specific node, say u, can receive its transmitted messages [3]. In this paper we assume that the adversary can compromise an arbitrary number of mesh nodes, through physical capture or software bugs, thus gaining full control of them. Once compromised, the adversary will extract all the security information stored in the compromised nodes as well as the encryption keys preloaded into their memories. The adversary can capture any message that is being sent by any of the compromised node's neighbors. If a message is encrypted

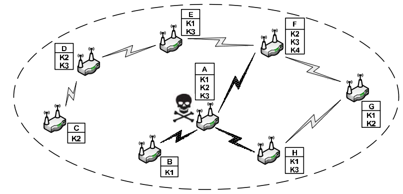


Fig. 2. Malicious eavesdropping attack

using any encryption key that is preloaded to the compromised node, in this case the adversary will be able to decrypt the message and extract its content.

To illustrate the attack, we will use an example in Fig. 2. In this example, 8 MRs are forming a WMN, in which, each MR is preloaded with a number of encryption keys. Note that, each node can communicate with its neighbor if they share at least one encryption key, the links in the figure correspond to the existence of shared keys between different nodes. Let us assume that node A has been compromised, in this case all the one hop neighbors of node A will be monitored by the compromised node (A). Monitored links are noted with black links in the figure. *When node F sends an encrypted message to node E using key ($K3$), due to the broadcast nature of wireless networks, and since node A lies within node F's transmission range and has the key ($K3$), the adversary at node A will listen to all the encrypted messages that comes out of node F using ($K3$).* The same thing would happen if node H is broadcasting a message to G encrypted with key ($K1$), as long as the compromised node (A) has this key, it will keep spying on all the messages in its neighborhood (*transmission range*) that is encrypted using ($K1$).

C. Motivations

In this section we discuss our motivations towards this work.

- In practice, when a node is compromised by an adversary, all the information stored in that node will be extracted by that adversary, including the set of encryption keys preloaded to that node. We realized that, *the way in which keys are assigned to/among all the nodes in the network could make the network resistant or vulnerable to malicious attacks* such as the one discussed in II-B.
  We observed that previously key management schemes did not consider the effect of sharing the same keys between nodes within a 2-hops neighboring range of a any node, say u. Due to the broadcast nature of wireless channels, when any neighboring node of u, say v, send a message M_k to any other node outside the communication range of node u, if this message is encrypted using key k which is shared between nodes u and v, then the adversary will be able to decrypt the message content using the keys extracted from the compromised node u. This attack has been discussed in II-B.
- Previous works [5][6] indicate that, to assign keys to nodes in a network, a large pool of keys must exist, from where a set of keys (K) is chosen randomly to be assigned to each node. We realized that, *not all the generated keys in the pool will be used, nor all the keys stored in some nodes*. Moreover, *the ratio between the pool size and the number of keys $|K|$ will affect the network*, where with

large ratio, more variety keys can be chosen from the pool for each node. If the process of generating encryption keys for the pool of keys is expensive, this will affect the key assignment scheme, in that the variety in choosing keys from the pool will be small, and that in turn will lead to having the same keys being shared between multiple nodes in the same neighborhood.

In this work, we aim to provide a key assignment scheme between the MRs, by assigning K available encryption keys *among* all nodes in a common neighborhood to be as different as possible such that the malicious eavesdropping attack can be reduced.

III. Problem Statement

In this section, we will formally state the definition of our optimization problem that we are going to study.

*Definition 3.1 (**Shared encryption key** ($Sk_{u,v}$)):* Given any two neighboring nodes $u, v \in G$, if there is an encryption key $k \in keys(u) \cap keys(v)$, then we can say that there exists a shared encryption key $Sk_{u,v}$ between node u and node v, where $keys(u)$ and $keys(v)$ are the sets of keys which are preloaded to node u and v respectively. □

*Definition 3.2 (**2-hop compromised nodes** ($2CN_u$)):* Given nodes $u, v, w \in G$, where v is a 1-hop neighbor of u, and w is a 2-hop neighbor of u via v. If node u has been compromised, the *2-hop compromised nodes* of node u ($2CN_u$) is defined as the set of nodes (w), for which node v sends messages encrypted by any key $k \in Sk_{u,v} \cap Sk_{v,w}$. □

*Definition 3.3 (**Node compromise ability** (NCA(u))):* Given a network G, we define the node compromise ability (*NCA*) for a compromised node $u \in G$, as the number of nodes in the set $2CN_u$. □

This is given in Eq. 1.

$$NCA(u) = |2CN_u| \tag{1}$$

*Definition 3.4 (**Malicious eavesdropping ability** (MEA)):* Given a network G with n nodes, where each node has been preloaded with a set of encryption keys. The *malicious eavesdropping ability* in the network is defined as the maximum *NCA* among all nodes in G. □

This is shown in Eq. 2.

$$MEA = max\{NCA(n) | n \in G\} \tag{2}$$

It is worth nothing that before encryption keys are given to each node, it is impossible to measure the malicious eavesdropping ability of the network. However, because the broadcast nature of wireless mesh networks, if we can distribute the encryption keys to be as different as possible, we could minimize the malicious eavesdropping ability in the network. Note that, different encryption key assignment can induce different corresponding communications, as well as increasing or decreasing the malicious eavesdropping ability. We formalize our secure key management scheme problem in the following:

*Definition 3.5 (**SKeMS** problem):* Given a network G and a set of encryption keys (K), the **S**ecure **Ke**y **M**anagement **S**cheme (**SKeMS**) seeks a key assignment design $\mathcal{A}$ such that the *MEA* in the network is minimized using $|K|$ encryption keys. □

IV. A Secure Key Management Scheme

In order to have a secure WMN that is resistant to malicious eavesdropping attacks, we in this work provide a secure key management scheme (SKeMS) that seeks to minimize the malicious eavesdropping ability (*MEA*) in the network. Our proposed solution is listed in Algorithm 1, the notation's description to be used in our scheme is given in Table I.

TABLE I
Notation used in our scheme description

Notation	Description
u, v, w	Nodes
NIR(u)	u's neighbors that have no common keys with u
K	A set of available encryption keys
k	An encryption key
$keys(u)$	A set of keys in node u

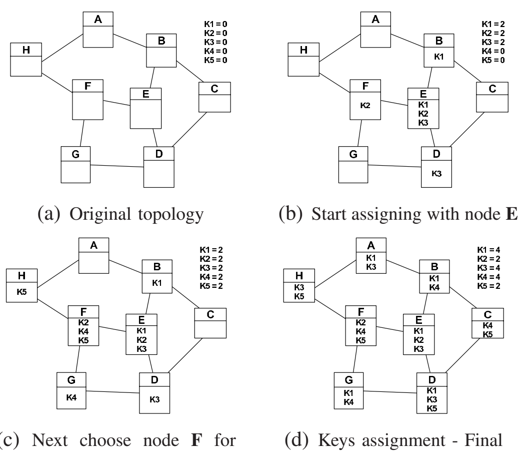
Given a network G and a set of encryption keys K, first in line 1, we initialize $keys$ in each node in G to the empty set. For all nodes in G, find node, say u, that has the highest number of neighbors that do not have common keys with u (Lines 3-4). After choosing the node with the highest *NIR* we start assigning the keys between that node and all its neighbors (Lines 7-16). *The idea in this key assignment design is that we try to assign the keys among the nodes to be as different as possible, while keeping the network connected.* After choosing the node to start with, say node u, we start taking node u and one of its neighbors, say v, as a pair of nodes and assign a key on both nodes to be used as a shared key for secure communication (Line 5-6).

Algorithm 1 Secure Key Management Scheme (G, K)

1: **for** each node $u \in G$ **do**
2: $keys(u) = \emptyset$;
3: **end for**
4: **for** all nodes in G **do**
5: **for** each node $u \in G$ **do**
6: Find *NIR*(u);
7: Calculate |*NIR*(u)|;
8: **end for**
9: Choose node $u \in G$ with the highest |*NIR*(u)|;
10: **for** each node $v \in$ *NIR*(u) **do**
11: //Assign keys between node u and node $v \in$ *NIR*(u) based on the following rules:
12: **if** $keys(u) = \emptyset$ and $keys(v) = \emptyset$ **then**
13: Choose k as the least used key from K;
14: Add k to $keys(u)$ and $keys(v)$;
15: **else if** $keys(u) \neq \emptyset$ and $keys(v) = \emptyset$ **then**
16: Choose k as the least used key from K not in $keys(w)$, where w is a neighbor of u, if applicable, else choose k as the least used key from K;
17: Add k to $keys(u)$ and $keys(v)$;
18: **else if** $keys(u) \neq \emptyset$ and $keys(v) \neq \emptyset$ **then**
19: Choose k as the least used key from K not on w where $w \in NIR(u) \cup NIR(v)$, if applicable, else choose the least used key from K;
20: Add k to $keys(u)$ and $keys(v)$;
21: **end if**
22: **end for**
23: **end for**

In lines 7-9, if the chosen pair of nodes u and v has not been assigned any key yet, we will choose the least used key from the set of available keys K and assign it on both nodes, so as to be used as an encryption key for their communications. If node u has previously been assigned some keys, in this case we will choose the least used key from K not been used on any neighboring nodes of node u or node v, so as to make the assignment as diffrent as possible. This idea can be seen clear in the example in Fig. 3. If node u has already assigned some keys, but it is not sharing any of them with node v. In this case we will choose the least used key from the available keys not in w, where node w is a neighbor of node u, which already share a key with node u. Then we will add the key to both u and v nodes. (Lines 10-12) If both chosen nodes have been assigned some keys but there is no shared key between them, in this case we will choose the least used key from K not been used on either u *or* v's neighbors, if applicable, else we will choose the least used key from K (Lines 13-15).

We use an example in Fig. 3 to illustrate our algorithm. For simplicity, we assume five keys available to be assigned among 8 nodes. Fig. 3(a) shows the original network topology. According to Algorithm 1, We start with node E, since node E has the highest number of neighboring nodes that do not share keys with it. In here we have nodes B, D and node F as node E's neighbors. Let us start with the nodes pair (E, B), we will refer to lines 7-9 in our algorithm. We choose the least used key from K, say key K1, and assigned it to both nodes. Next we will follow the same steps before to assign keys between nodes E, C and E, F. This assignment can be seen in Fig. 3(b).



(a) Original topology

(b) Start assigning with node **E**

(c) Next choose node **F** for assigning

(d) Keys assignment - Final

Fig. 3. Secure key management scheme (SKeMS) example

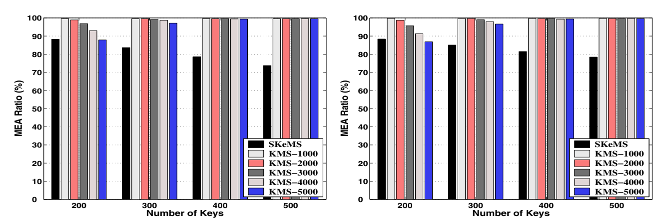
Our next step is shown in Fig. 3(c). We choose node F to continue the key assignment, since node F has the highest *NIR* among all the nodes in the network. It can be seen that node F and G has no shared key among them, but since node F has some keys, we will try to assign a new key between these two nodes to have a different key assignment that can stands among the malicious eavesdropping attacks. In this case we follow our algorithm in lines 10-12 to assign the keys. Since node E which is node F's neighbor is using keys (K1, K2, K3) for encryption, and node D which is node G's neighbor is using key K3, we will choose the least used key from K which is not been used on nodes E and D, in here we choose K4 as the encryption key between node F and node G. We followed the same steps to assign a key between node F and node H, where we choose K5 as the encryption key between them.

Our SKeMS design aims to minimize the *MEA* of the network, where in Fig. 3(d) after our key assignment design we minimize the *MEA* to 1.

V. Numerical Results

To illustrate the performance of our scheme, we implemented our solution (denoted by **SKeMS** in the figures), and compared it with previous scheme in [5] (denoted by **KMS** in the figures). We considered static WMN with n nodes uniformly distributed in a square playing field. Each node has a fixed transmission range of $250m$. The results shown are the average of 5 test runs for various scenarios.

The first metric used for performance evaluation is *malicious eavesdropping ability ratio* (denoted as *MEA ratio* in the figures), which is calculated as the neighbor compromise ability (*NCA*) divided by the total number of neighboring nodes that are vulnerable to eavesdropping attack (discussed in subsection II-B). *Having smaller MEA ratio indicates that the network is more secured and more resistant against malicious eavesdropping attacks*. In our first tested scenario, we randomly distributed 300 and 400 nodes in a $10x10^5$ square meters. To achieve better security for KMS scheme, we provide different pool sizes ranges from (1000−5000) keys. *Note that, having different pool sizes doesn't affect our SKeMS scheme*. Our first scenario's results are shown in Fig. 4.



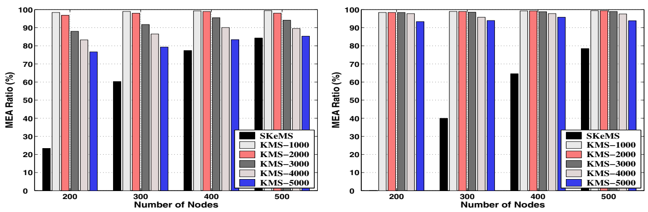
(a) 300 nodes in $1000m$x$1000m$

(b) 400 nodes in $1000m$x$1000m$

Fig. 4. Different keys

Fig. 4(a) shows the *MEA ratio* versus different number of keys ranges from (200−500) keys. In our proposed scheme, we used available keys to assigned keys among all nodes. On the other hand, in the KMS, each node will store the available number of keys which are chosen randomly from the provided key pool. For the KMS scheme increasing the pool size will minimize the *MEA ratio*. For example, with 200 keys chosen from a pool size of 1000 keys, we have an *MEA ratio* of 98%, while with 5000 keys pool size with the same number of keys we have a ratio of 87%. Compared to our scheme, the results show that our scheme outperforms the KMS scheme in all different tested pool sizes. For example, with 300 keys, our scheme has an *MEA ratio* of 82%, where by using the KMS scheme with 5000 pool size we got a ratio of 97.6%. These results also show that, by increasing the number of available keys, we can provide a better *MEA ratio*. For example, with

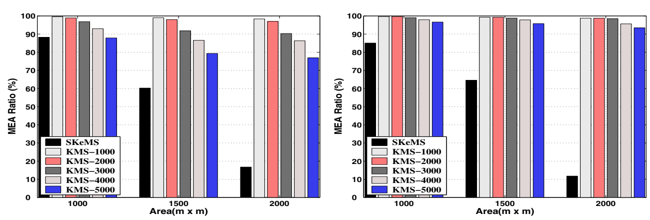
200 keys, the ratio is 86%, while with 500 keys it drops to 73%. The same results' trend can be seen in Fig. 4(b), where we distribute 400 nodes in a 1000m square field.



(a) 200 Keys in a 1500mx1500m (b) 400 Keys in a 1500mx1500m

Fig. 5. Different nodes

Fig. 5 show the results of our second scenario in which we studied the schemes' performance when having different number of nodes in the same area size. In Fig. 5(a) we tested the performance with different number of nodes (200−500 nodes) distributed in a $225x10^4$ square meters. We tested the effect of assigning 200 keys on the *MEA ratio* on the specified network. The results show that, by applying our SKeMS scheme, the *MEA ratio* is increasing while the number of nodes is increasing due to having more common shared keys between the nodes in the neighborhood. But our scheme's ratio is still better compared with the *MEA ratio* when applying the KMS scheme. The same results' trend can be seen in Fig. 5(b), with 400 keys to be assigned.

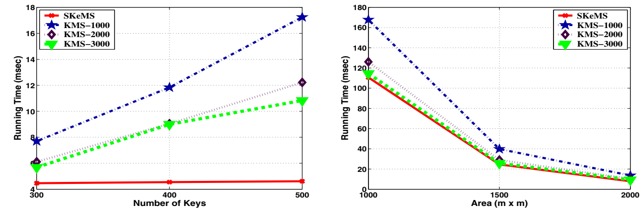


(a) 300 nodes with 200 keys (b) 400 nodes with 300 keys

Fig. 6. Different area sizes

In Fig. 6 we tested the effect of the network density (*the number of nodes in one square unit*) on both schemes by changing the area size to be (1000, 1500 and 2000 square meters), while keeping the number of nodes fixed. Fig. 6(a) shows the case with 300 nodes distributed in different area sizes with 200 available keys. The results show that in sparse network, the number of neighboring nodes became smaller with increasing the area size, this indeed decreases the number of nodes that can be affected with the eavesdropping attack. The same trend can be seen in Fig. 6(b) with 400 nodes and 300 keys.

The second performance metric is the *running time*, which is defined as the running time that the scheme took to assign the keys among the nodes. We tested our scheme and compared it with the KMS scheme in two different scenarios shown in Fig. 7. Our first scenario is shown in Fig. 7(a), where 200 nodes are randomly distributed in a 1500 square meters field size. We assign 300, 400 and 500 keys for both schemes. Since the KMS scheme depends on the pool size, with different pool sizes, it can be seen that it takes more time to assign the keys from 1000 keys pool size and find the *MCA* of the network, due to having more number of neighboring nodes that share more common keys. Compared to our scheme, it can be seen that our scheme outperforms the KMS scheme in all tested cases.



(a) Running time (200 nodes in 1500m^2) (b) Running time (300 nodes with 400 keys)

Fig. 7. Running time

The second scenario is shown in Fig. 7(b), in which, we changed the network density by changing the area size from 1000 to 2000 square meters. It can be seen that our SKeMS scheme provides a more secured network in less time compared to the KMS scheme. We tested the KMS scheme with 1000, 2000 and 3000 key pool sizes.

VI. Conclusion

In this paper, we defined the **S**ecure **K**ey **M**anagement **S**cheme (SKeMS) problem, and presented an effective solution that provide a key assignment to a wireless mesh network. Our solution is resistant against malicious eavesdropping attacks. Simulation results showed that our solution performs well in terms of smaller malicious eavesdropping ability ratio and less running time. To sum up, in this paper, we showed that a good key management scheme can ensure a more secure network.

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