HASH GRAPH BASED KEY PREDISTRIBUTION SCHEME FOR MOBILE AND MULTIPHASE WIRELESS SENSOR NETWORKS

by

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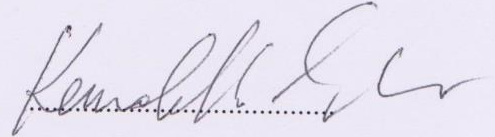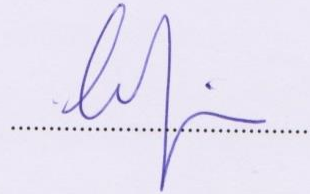
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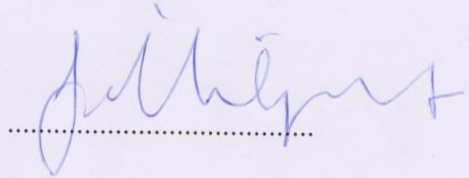
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Abstract

Wireless Sensor Networks (WSN) consist of small sensor nodes which operate until their energy reserve is depleted. These nodes are generally deployed to the environments where network lifespan is much longer than the lifetime of a node. Therefore, WSN are typically operated in a multiphase fashion, where new nodes are periodically deployed to the environment to ensure constant local and global network connectivity. Besides, significant amount of the research in the literature studies only static WSN and there is very limited work considering mobility of the sensor nodes.

In this thesis, we present a key predistribution scheme for mobile and multiphase WSN which is resilient against eager and temporary node capture attacks. In our Hash Graph based (HaG) scheme, every generation has its own key pool which is generated using the key pool of the previous generation. This allows nodes deployed at different generations to have the ability to establish secure channels. Likewise, a captured node can only be used to obtain keys for a limited amount of successive generations. We also consider sensor nodes as mobile and use different mobility models to show its effects on the performance. We compare the connectivity and resiliency performance of our scheme with a well-known multiphase key predistribution scheme and show that our scheme performs better when the attack rate is low. When the attack rate increases, our scheme still has better resiliency performance considering that it requires less key ring size compared to a state-of-the-art multiphase scheme.

ÇOK FAZLI VE MOBİL KABLOSUZ DUYARGA AĞLARI İÇİN TASARLANMIŞ ÖZET ÇİZGESİ TABANLI ÖNYÜKLEMELİ ANAHTAR DAĞITIM ŞEMASI

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Özet

Kablosuz Duyarga Ağları (KDA), duyarga düğümü adı verilen ve enerji kaynakları kısıtlı olan küçük aygıtlardan oluşur. Bu düğümler genellikle ağ ömrünün duyarga düğümünün pil ömründen çok daha fazla olduğu ortamlarda konuşlandırılırlar. Dolayısıyla KDA'lar yerel ve genel bağlantı oranlarını sabit bir değerde tutmak için ortama sürekli yeni düğümlerin konuşlandırıldığı çok fazlı bir biçimde çalışmaktadırlar. Bunun yanısıra, literatürdeki araştırmaların önemli bir kısmı statik KDAlar üzerine yapılan çalışmaları içerirken, duyarga düğümlerinin mobil olması durumunu değerlendiren çok kısıtlı çalışma bulunmaktadır.

Bu tezde, mobil ve çok fazlı KDAlarda kullanılmak üzere tasarlanmış, sürekli ve geçici düğüm ele geçirme saldırılarına karşı dayanıklı bir anahtar ön dağıtım şeması sunulmaktadır. Önerilen Özet Çizgesi Tabanlı (ÖÇT) şemada, bütün nesillerin kendilerine ait bir anahtar havuzu bulunmaktadır. Bu havuzlar önceki neslin anahtar havuzu kullanılarak üretilmekte, ve bu sayede farklı nesillerde konuşlandırılan düğümler birbirleriyle iletişim kurma imkanı bulmaktadırlar. Ayrıca, ele geçirilen bir düğüm sadece kısıtlı bir sayıdaki ardışık nesillerin anahtar havuzlarından ufak bir miktarda anahtarı ifşa etmektedir. Önerilen şema ile iyi bilinen bir şema arasında karşılaştırmalı analizler gerçekleştirilmiş ve saldırı oranı düşük olduğu durumda önerilen şemanın çok daha iyi dayanıklılık performansı sergilendiği gözlemlenmiştir. Saldırı oranı artırıldığında da, karşılaştırılan şemadan daha az anahtar kullanarak aynı yerel bağlantı oranı yakalandığı gözlenmiş ve yine daha iyi oranda dayanıklılık performansı görülmüştür.

To my family

Acknowledgements

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Chapter 1

Introduction

Wireless Sensor Networks (WSN) are composed of sensor nodes which have limited amount of memory, energy and computation power. In typical application settings, sensor nodes are spread randomly over an environment and collect data that is transferred to a trusted central point for further examination [4]. Most of these application scenarios require long term sensing of the environment and energy reserve of the sensor nodes last for a very limited time. Therefore, deploying new nodes to the environment in certain intervals, called *generations*, is the only way to have stable network connectivity. Since the network lifespan is much longer than the lifetime of a sensor node, it is most likely that we have multiple generations while sensing an environment. Networks that provide this property are called *Multiphase* WSN.

Security of the communication between sensor nodes becomes an important criterion when WSNs are deployed in hostile environments. Wireless nature of the communication has both advantages and disadvantages on the network. A sensor node can easily create communication links with its neighboring nodes, however this link can be intercepted by an intruder and the transferred information can be eavesdropped by

means of third party attackers. One other security risk is that these nodes are often deployed unattended. They are left to the environment and not checked for a long time. Therefore, they are open to physical attacks as well. These security problems and some other ones are addressed in [11] and many researchers have studied security related issues in relation to WSN deployments.

These security problems encountered in WSN are addressed by applying cryptographic primitives on the data that is transferred over the communication link. As we have pointed before, sensor nodes have limited resources; therefore, it is not possible to use cryptographic mechanisms requiring high computational power, such as public key cryptography. Instead, symmetric key cryptography approaches are employed in WSN to provide security. Symmetric key cryptography is more CPU-efficient and does not require high amount of computational power and energy. However, sensor nodes collect excesive amount of data and it is not feasible to transfer this data to the base station one at a time. As an alternative, sensor nodes should have the capability to process the data before transferring it to the base station. When a sensor node receives some encrypted information from its neighbor, it should be able to see the data and fuse it with its own collected information before transferring it to other nodes. This entails that the keys need to be shared among the sensor nodes. In other words, secure communication between WSN nodes should be possible.

There exists many different key agreement protocol proposals for WSNs and we can organize them in three groups: (i) trusted server approaches, (ii) public key cryptography based mechanisms and (iii) key predistribution schemes. Among these, key predistribution approach is the most viable method for WSNs [11]. In key predistribution schemes, keys are distributed to all sensor nodes prior to deployment and nodes use these keys to create secure communication links. There exist various solutions in this category such as single master key, full pairwise [5], probabilistic [5, 6] and deterministic [7, 8, 12] approaches. These key predistribution schemes try to balance the two important metrics for sensor networks: network connectivity and resiliency against node capture attacks.

In some application scenarios, WSNs should be considered as mobile and sensor nodes should be able to adapt to rapid changes in the network. Introducing mobility to sensor

nodes in WSN can enhance its capability and flexibility to support multiple missions and handle many of the problems mentioned before. Sensors can be attached to people for health monitoring, which may take account of the heart rate, blood pressure etc. However, most of the key predistribution schemes in the literature are proposed for static and single phase WSN. There exist a handful of research efforts for mobile WSNs [14, 18-21] but none of them considers a multiphase network.

1.1.   Our Motivation and Contribution of the Thesis

In the literature, most of the proposed key predistribution schemes are designed for single phase WSN and ignore the fact that sensor nodes have very limited amount of battery power. Since the battery of sensor nodes deplete in a very short time, deploying new sensor nodes to the environment in multiphase fashion is essential in maintaining long term surveillance. One other problem of the single phase WSN solutions is node additions to the network. Although they allow node additions to the network when the deployed sensor nodes die, this operation is not stress-free and secure. Modification of single phase WSN key predistribution solutions to adapt multiphase WSN has the weakness of continuous usage of the same list of keys for multiple generations. Keys captured by an attacker at any time can be used in the course of the network's operation time. However, with multiphase WSN, we can use different generation key lists that are completely different from the key lists used in other generations. This way, an attacker would only be able to compromise some portion of the network and after some time, the percentage of the compromised nodes will become stable if the attack is permanent. To the best of our knowledge, there are only a few key predistribution schemes [1-4, 9-10] addressing multiple deployments of the sensor nodes, which is called multiphase WSN.

One other thing about the WSN deployments is that sensor nodes are often perceived as static. There is very limited work that considers sensor nodes as mobile [14]. However, it is very likely that these nodes will be deployed to the environments where natural effects will cause them to move from one location to the other. Therefore, key predistribution schemes should also consider the mobility of the WSN [14]. There exist several entity and group mobility models for sensor networks and they are categorized as entity and group mobility models. Entity mobility models consider each sensor node

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individually, whereas group mobility models form sets of nodes [13]. In our study, we have used Random Walk Mobility model as entity model and Reference Point Group Mobility model as the group mobility model. We have also used Circular Move Mobility model, which is in between entity and group mobility models, because it considers each sensor node independently but the nature of the environment forces nodes to move in groups. Circular Move Mobility model is an environmentally friendly hybrid mobility model that is first proposed by our research group and we describe its model in detail.

In this thesis, we present a new key predistribution scheme which is based on hash graphs of keys and it provides better secure connectivity between sensor nodes deployed at different generations. In our Hash Graph based (HaG) scheme, each deployment generation has its own key pool and these pools are generated using the pool of the previous generation. Key pool of the first generation is randomly generated and the subsequent generations use two consecutive keys of the preceding generation to form a key for the next generation. More specifically, two sequential keys are XORed (i.e. logical Exclusive Disjunction operation) and hashed together using a secure hash function to constitute a key of the next generation key pool. When two nodes are in the communication range, they use the generation that they have been deployed to the network in conjunction with the identification numbers to decide whether they have a common key or not. If they can find at least one common key, then nodes perform XOR operation on all common keys to generate a direct link key that is used for secure communication. With the HaG scheme, a temporary attacker can only compromise some portion of the network and right after the attack stops, scheme self-heals the keys until the compromised key ratio decreases to zero. Similarly, an eager attacker is only able to compromise some steady fraction of the network. Attack models and network resiliency metrics are described in performance evaluation section. Compared to other multiphase schemes, HaG scheme provides better in resiliency if the attack rate is low. If the attack rate is high, we have some considerable improvements on the resiliency as well. Using a smaller amount of keys, HaG scheme delivers same connectivity rate with better resiliency performance.

1.2. Organization of the Thesis

The rest of this thesis is organized as follows. Chapter 2 summarizes existing key predistribution methods and gives background information about the mobility models. In Chapter 3, we provide detailed information about the scheme that we propose. Chapter 4 discusses the comparative performance analysis of our scheme and RoK scheme. Finally Chapter 5 concludes the thesis.

Chapter 2

Background Information

In this section, we give background information on Wireless Sensor Networks and describe their security requirements. Then we summarize previously proposed key predistribution schemes that provide these requirements. We also give details of the mobility models that we have used to evaluate the performance of our proposal.

2.1. Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) consist of small devices which are deployed to different environments in large numbers [4]. These devices, called sensor nodes, are very small with limited memory, battery power, bandwidth, transmission range, and computational power. A WSN is distributed to an environment without any prior knowledge of the network topology. Sensor nodes, once deployed, search for their neighboring nodes and try to transmit the gathered information to some limited amount of Base Stations (BS) available in the network. These BS collect all the information from the network for further analysis.

Sensor nodes have a wide variety of applications in both military and civilian areas. They are being used to collect many type of information from different of environments, such as magnetic, acoustic, temperature, seismic etc. Nevertheless, data in the sensor nodes deployed in military, health care, or some commercial applications need to be securely transmitted. The interception of such data can cause bad circumstances and therefore it must be prevented by taking some actions. Wireless nature of the communication, resource limitation on sensor nodes, very large and dense deployments, lack of fixed infrastructure, unknown network topology before deployment, and high risk of physical attacks to unattended sensor nodes are just a few challenges to the security of WSNs [4, 22-23].

2.2. Security Requirements of Wireless Sensor Networks

For security reasons, cryptographic keys must be stored in sensor nodes and they should have the ability to carry out secure communication. Therefore key management becomes an important problem in WSNs. The key establishment techniques must incorporate the following properties [15-17]:

- *Availability:* Guaranteeing that the service offered by the whole WSNs is available whenever required.

- *Authenticity:* Ability to verify that the message sent by a node is authentic.

- *Confidentiality:* The key establishment method should safeguard the disclosure of any data from the network to any unauthorized third party.

- *Flexibility:* Key establishment method should allow adding new nodes at any time and it should be useful in multiple applications.

- *Scalability:* Key establishment method should allow for the variations in the network size.

- *Integrity:* Ensuring that the data transmitted by any node is not modified by any unauthorized third party.

- *Non-repudiation:* Ability to prevent malicious nodes from hiding their activities.

- *Time Synchronization:* Ability to synchronize time between different sensor nodes.

Similarly, security protocols for WSNs have the following constraints and requirements. These issues should be kept in mind while designing a new key establishment protocol [17]:

- *Memory:* Number of keys required for secure communication in the network should be as small as possible.

- *Computational power:* Computational overhead of the key establishment process should be as low as possible.

- *Scalability:* It should be possible to add new nodes to the network as needed.

- *Communication power:* Key establishment process should limit the amount of broadcast information.

- *Secure communication:* Probability that two neighboring sensor nodes share some common key for secure communication must be high.

- *Resiliency:* When a node is captured by an attacker, the impact of this compromised node on the rest of the network should be as low as possible.

2.3.   Hash Functions

In order to provide the security of the keys in our key predistribution proposal, we use cryptographic mechanism called *hash* functions. Hash functions are basic components of many cryptographic algorithms and they can be used to make many algorithms more efficient. In this section, we discuss the basic properties of secure hash functions. However, these hash functions should bear some security properties.

A secure cryptographic hash function, H, takes an input message of arbitrary length and produces an output *message digest* of fixed length. More formally, a hash function can be defined as:

$$h = H(m) : \{0,1\}^* \rightarrow \{0,1\}^n$$

where m is the input message of arbitrary length and h is the output message digest of length n.

Secure hash functions must have the following special characteristics:

i. *Computability:* Given a message m, it should be very easy and fast to calculate the message digest $h = H(m)$.

ii. *One Way Property:* Given a hash $h = H(m)$, it is computationally infeasible to find the message m.

iii. *Weak Collision Resistance:* Given a hash h, it is computationally infeasible to find a message m', such that $h = H(m')$. Note that we are not trying to find the exact message that has the hash value h. Instead, this property indicates that finding some message m', which has the same hash $h = H(m')$ value, should be hard.

iv. *Strong Collision Resistance:* Given a message m, it is computationally infeasible to find another message m', such that $H(m) = H(m')$.

It is clear from the formal description that the set of possible input messages is much larger than the set of possible message digests. Therefore, there should always be many examples of messages m_1 and m_2 with $H(m_1) = H(m_2)$. Requirement iv. says that it should be hard to find these examples, but it does not claim that it should be impossible to find another message with the same message digest value.

In our key predistribution scheme, we are using a hash functions to calculate keys using a set of other keys. There are many secure hash functions available in the literature, such as MD5 [26], SHA-1 [24] and SHA-2 [25]. MD5 algorithm is no longer secure; therefore, SHA-1 is preferred in this work.

2.4.   Key Predistribution Schemes

Depending on the application area of the WSN, security of the communication becomes an important criterion. Different key agreement protocols have been suggested for WSNs and we can organize them in three groups: trusted server, public key and key predistribution. It has been discussed by different researchers and shown that out of these three suggestions, key predistribution approach is the most suitable method for WSNs [4-6, 11-12, and 28-32]. In key predistribution schemes, keys are distributed to all sensor nodes prior to deployment and nodes use these keys to create secure communication links. There exist various solutions to the key predistribution problem, such as single master key, full pairwise [5], probabilistic [5, 6] and deterministic [7, 8, 12] approaches.

In single master key approach, a master key is predistributed to all nodes and used all the time. Though this method is simple and has perfect connectivity between nodes, it has very bad network resilience. Once the attacker captures this key, the security of the entire network becomes compromised. Full pairwise scheme proposed by Chan et al. loads $n-1$ pairwise keys to every node of the n nodes in the network [5]. Although this scheme provides high level of security, it requires high amount of memory on the sensor nodes to store pairwise keys. Besides, addition of new nodes to the network is only possible if pairwise keys of them are preloaded to the nodes that are deployed before. Therefore, these naive approaches are not suitable for WSNs security.

In probabilistic schemes, nodes receive a group of randomly selected keys, amount of which is enough for having a good connectivity percentage over the network. Although probabilistic schemes are less secure compared to the full pairwise scheme, they circumvent the memory overhead and require nodes to store only some predefined amount of keys in their memory. Practically all of the probabilistic schemes have three stages: (i) key predistribution, (ii)shared key discovery and (iii) path key establishment. Eschenauer and Gligor's well-known Basic Scheme [6] is one example for the probabilistic schemes. In key predistribution phase, each sensor node is loaded with τ keys that are randomly selected from a key pool of size P where $\tau \ll P$. After deployment, sensor nodes try to discover their neighbors. When two neighboring nodes

find at least one common key, then they can create a direct link to communicate securely. If no common key exists, then nodes start the path key establishment phase and they try to create a direct link with the help of their common neighbors. When we evaluate the performance of the Basic scheme, since $\tau \ll P$, majority of the keys will be loaded on multiple nodes and this decreases the resiliency. Finding neighbors with common keys, called local connectivity, is also an important performance criterion. Therefore, the value of τ should be selected wisely to balance resiliency and local connectivity. Considering this weakness of the Basic Scheme, Chan et al. [5] have proposed a modification on the Basic Scheme, known as q-Composite Scheme, which requires two nodes to have at least $q > 1$ keys in common in order to establish a secure direct link. This improvement increases the resiliency of the scheme, but decreases the connectivity of the network.

In the literature, we also have deterministic key predistribution approaches which are developed from the idea of Blom [7]. Generating one public and one private matrices and storing only $\lambda + 1$ keys from these matrices allow the nodes to generate a secure direct key with any of the nodes in the network. However, compromising more than λ nodes in the network will compromise all of the keys used in the network. Du et al. [8] propose a combination of the Basic Scheme [6] and Blom's Scheme [7] without increasing λ value. This Multiple Space Key Predistribution scheme provides very good resilience but it has higher memory requirement and communication overhead.

One other deterministic approach is proposed by Camtepe and Yener (C-Y scheme) [12] and they are the first to apply combinatorial design to key predistribution problem. They have presented two different combinatorial designs: symmetric balanced incomplete block designs and generalized quadrangles. Their design includes points and blocks as distinct key identifiers and nodes. Although they have increased connectivity of the network compared to other schemes, their proposal is limited in network size and resiliency measures.

Up to now, all discussed key predistribution schemes are intended for single phase WSN. Even though they allow node additions to the network, it is not a stress-free and secure operation. Furthermore, modification of single phase WSN key predistribution

solutions to adapt multiphase network has the weakness of continuous usage of the same key pool for multiple generations. Keys captured by an attacker at any time can be used in the course of the network's operation time. However, with multiphase WSN, we can use different generation pools that are completely different from the key pools used in other generations. This way, an attacker would only be able to compromise some portion of the network and after some time, the percentage of the compromised nodes will become stable if the attack is permanent. To the best of our knowledge, there are only a few key predistribution schemes addressing multiple deployments of the sensor nodes, i.e. multiphase WSN [1-4, 9-10].

Robust Key predistribution (RoK) scheme is proposed by Castelluccia et al. [1] for multiphase WSN. This scheme increases the network resiliency increases without reducing secure connectivity. The RoK scheme improves the security by limiting the lifetime of the key pools and by refreshing the keys in time. RoK has forward and backward key pools for each generation; referred as FKP and RKP respectively. Keys in these pools are randomly generated and they are updated in forward and backward orders by hashing.

We know describe the key establishment process of RoK scheme and the symbols we use are listed in Table I below.

Table 1 - List of symbols used in RoK scheme

Symbol	Definition
P	Key pool size
FKP^j	Forward key pool at generation j
BKP^j	Backward key pool at generation j
FKR_A^j	Forward key ring of node A at generation j
BKR_A^j	Backward key ring of node A at generation j
fk_t^j	Forward key with index t at generation j
bk_t^j	Backward key with index t at generation j
kg_t^j	Key group with index t at generation j
sk_{AB}^j	Direct link key between nodes A and B for generation j
$h(\cdot)$	Secure hash function $h: \{0,1\}^* \rightarrow \{0,1\}^{160}$

To put it in more concrete terms for comparison with our proposal, forward and backward key pools of the RoK scheme at generation j is denoted as follows:

$$FKP^j = \left\{fk_1^j, fk_2^j, fk_3^j, \dots, fk_{P/2}^j\right\}, \tag{1}$$

$$BKP^j = \left\{bk_1^j, bk_2^j, bk_3^j, \dots, bk_{P/2}^j\right\}, \tag{2}$$

where P is the key pool size, as it is given in Table 1 below.

Then forward and backward key pool at the next generation $j + 1$ is defined as follows:

$$FKP^{j+1} = \left\{fk_1^{j+1}, fk_2^{j+1}, fk_3^{j+1}, \dots, fk_{P/2}^{j+1}\right\} \tag{3}$$

$$BKP^{j+1} = \left\{bk_1^{j+1}, bk_2^{j+1}, bk_3^{j+1}, \dots, bk_{P/2}^{j+1}\right\} \tag{4}$$

Although they look similar in formulation, there is an important difference between the keys in these pools. Forward keys in the generation $j + 1$ are generated by just performing a simple hash operation over the keys in the previous generation. However, backward keys in the generation $j + 1$ are used to generate the keys in the generation j by performing the same hash operation. These operations are denoted as follows:

$$fk_i^{j+1} = h\left(fk_i^j\right) \tag{5}$$

$$bk_i^j = h\left(fk_i^{j+1}\right) \tag{6}$$

Nodes are loaded with equal number of keys having the same key identifier from forward and backward key pools. Lifetime of node is constrained by $i + G_w$ generations where i is the deployment generation of the node and G_w is the generation window. A node can only produce forward keys for generation j where $j > i$, and backward keys for generation j where $j < i + G_w - 1$. Therefore, a node A deployed at generation j will carry two key rings: forward and backward key rings. The forward key ring FKR_A^j contains randomly selected forward keys from FKP^j. Similarly, the backward key ring BKR_A^j contains randomly selected backward keys from BKP^{j+G_w-1}. Key ring of the node A is defined as $kr_A^j = \left(FKR_A^j, BKR_A^j\right)$ and these key rings are denoted as follows:

$$FKR_A^j = \{fk_t^j | t = f(id_A || i || j), i = 1,2,3, \ldots, m/2\} \tag{7}$$

$$BKR_A^j = \{fk_t^{j+G_w-1} | t = f(id_A || i || j), i = 1,2,3, \ldots, m/2\} \tag{8}$$

As it can be observed from these key rings, node A can only update its key ring kr_A^i for the generation i between j and $j + G_w$. Here, we shall assume that there is a second node B and both nodes have common key indexes of $t_1, t_2, \ldots, t_z$. This means that they can compute all the forward keys $\{fk_\tau^\gamma | \tau = t_1, t_2, \ldots, t_z, \gamma = j, j + 1, \ldots, i + G_w - 1\}$ and all backward keys $\{bk_\tau^\gamma | \tau = t_1, t_2, \ldots, t_z, \gamma = j, j + 1, \ldots, i + G_w - 1\}$. Therefore, node A and B can compute the following secret key and use it to encrypt the communication link between them:

$$sk_{AB} = h(fk_{t_1}^j || bk_{t_1}^{i+G_w-1} || fk_{t_2}^j || bk_{t_2}^{i+G_w-1} || \ldots || fk_{t_z}^j || bk_{t_z}^{i+G_w-1}) \tag{9}$$

When two nodes are in communication range, they exchange their generation number and node identifier. Using these values, they calculate the identifier of the keys that are loaded on the node to be communicated and if they find at least one match, then they create the session key and start the secure communication. When an attacker captures a node from generation i, he would only be able to compromise keys that are used between generations $]i, i + G_w[$ because of the generation window boundary. Therefore, attacker should be continuously capturing at some rate permanently to have some portion of the network compromised. In the formulation (9), forward keys provide forward secrecy, meaning attacker will not be able to learn previous keys even if it learns a forward key from this list. Similarly, backward keys provide backward secrecy and the attacker will not be able to learn any future keys between nodes. Even though the attacker permanently captures nodes, he would only be able to compromise some portion of the network and as soon as he stops the captures, this percentage will start decreasing and become zero after some time. However, RoK scheme requires number of generations to be determined before starting the network because of the offline backward key pool generation phase. Also, sensor nodes use high computational power to update forward keys at every generation time.

Random Generation Material (RGM) scheme [2-3] is another multiphase WSN key predistribution method proposal. RGM scheme has one key pool for every generation and there is no relation between key pools of different generations. Nodes are loaded with keys from their deployment generation key pool. Communication between nodes deployed at different generations is provided with keys that are generated by XORing the keys between the generations of these two nodes. Then the XORed key is hashed and used to create a direct link between two nodes that are deployed in different generations. Compared to the RoK scheme, RGM has better resiliency because keys compromised from two nodes are only used in the generations that these nodes are deployed. Also, RGM has no limit on the deployment of the number of nodes to the network. However, increasing G_w value also increases the communication and computation cost of this scheme.

2.5.   Mobility Models

WSNs are deployed randomly to different environments and they build an ad-hoc network of sensor nodes. Significant amount of the research in the literature is considering these nodes to be stationary. In real world, nodes are deployed to environments where natural forces may affect the position of the node. Usually, the communication network is expected to have the ability to adapt to modifications, such as movements caused by the dynamics in the nature [13]. One important thing to note here is that sensor nodes are assumed to be unaware of their position data and they cannot form a multi-hop routing table that can be used all the time. Therefore, every time a node wants to transmit information gathered from the environment, it is expected to search for other nodes to which there is a secure communication line exists. It is clear that if all nodes are moving, then WSNs are more likely affected by the mobility.

In this study, we have used Random Walk Mobility (RWM), Reference Point Group Mobility (RPGM), and Circular Move Mobility (CMM) models while performing our analyses. RWM and RPGM mobility models have been used in the literature before and cited in some surveys [13], but CMM is newly proposed by our research group.

2.5.1. Random Walk Mobility Model

In Random Walk Mobility Model (RWM), a mobile sensor node moves from its current location to a new location by randomly selecting a direction and speed from pre-defined ranges, $[speedmin, speedmax]$ and $[0, 2\pi]$ respectively. Each movement in this model occurs in a constant time interval t, at the end of which a new direction and speed values are calculated. When a node reaches the boundary of the environment that it is deployed, it bounces off the border with the reverse angle that it was moving from and continues to move in the area. The Random Walk Mobility Model is in "entity" mobility mode class in the literature because it considers each node independent of others [13].
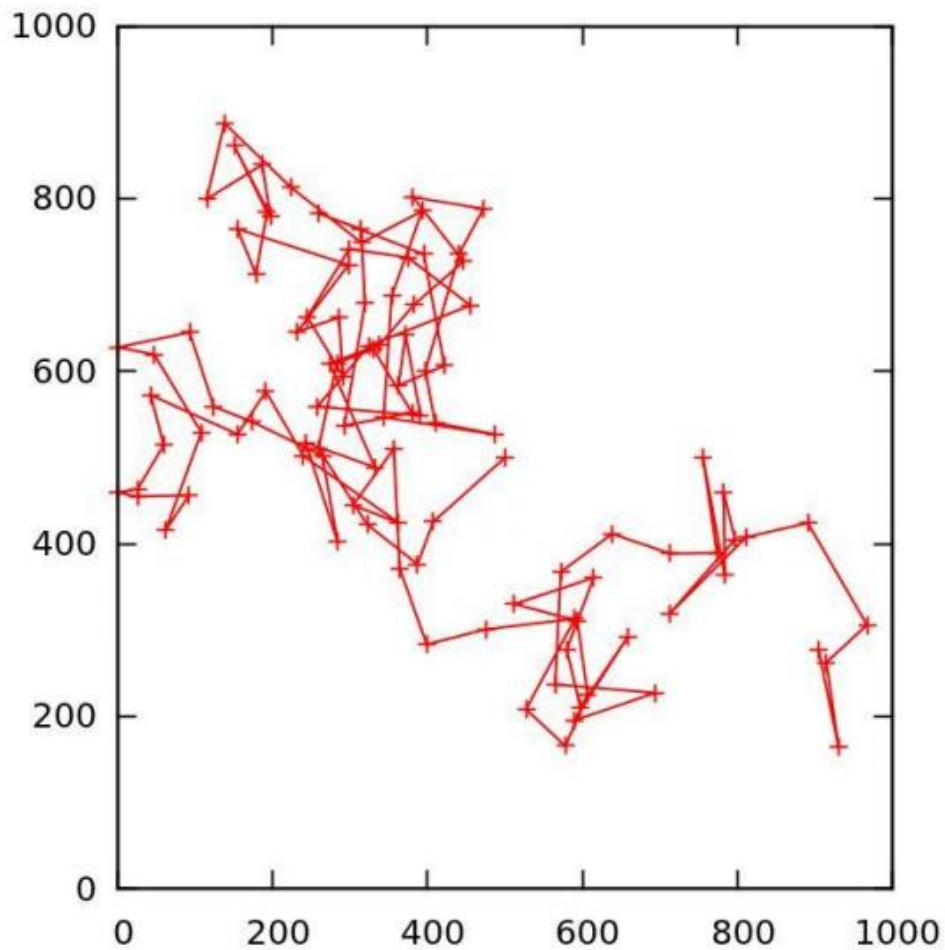
Figure 1 - Movement pattern of a single node using Random Walk Mobility model

2.5.2. Reference Point Group Mobility Model

In Reference Point Group Mobility Model (RPGM), sensor nodes move in groups and their movement is based upon the path traveled by a randomly selected logical center node. This center node moves according to an entity mobility model, which we have selected as the Random Walk Mobility Model in our study. Each node is assigned a reference point which follows the movements of the center node and they try to move within a pre-defined range around the center. Every node randomly moves from its current location to its next location based on its reference point. Therefore, RPGM model allows independent random motion behavior for each node that is performed inside the bounds of a group motion. The Reference Point Group Mobility Model is one of the widely used group mobility model because it is possible to choose different entity mobility models as the movement pattern of the logical center.
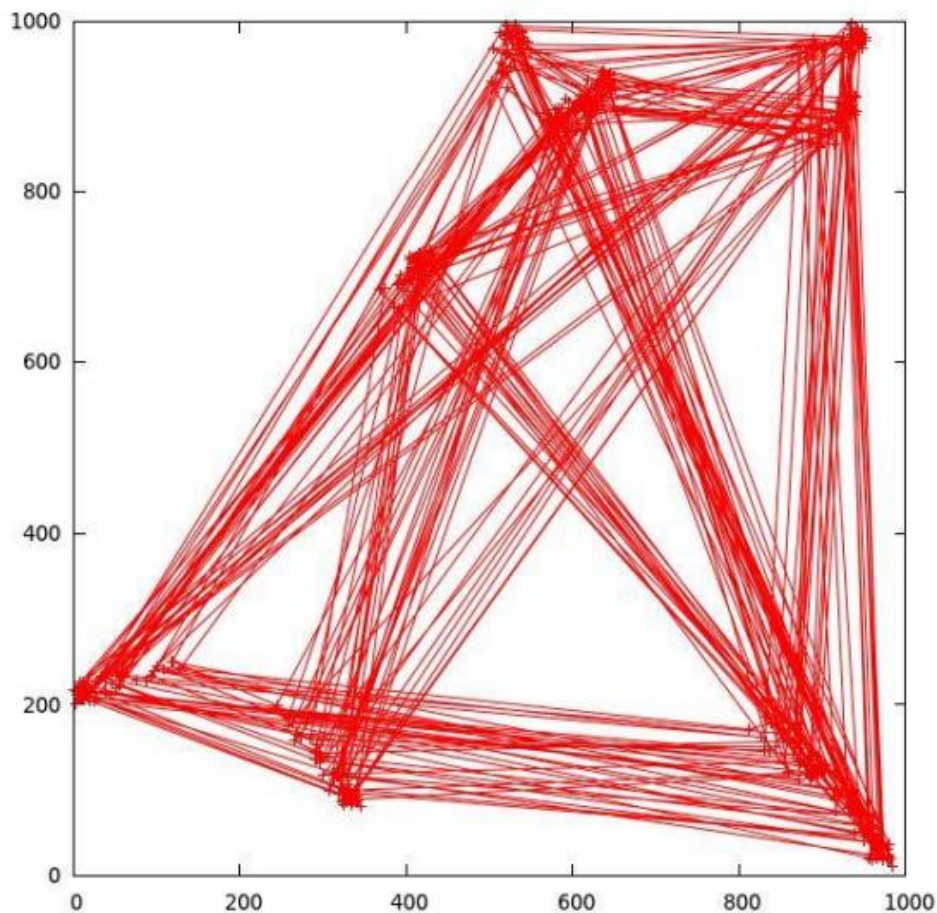
Figure 2 - Movement pattern of a group with ten nodes using Reference Point Group Mobility model

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2.5.3. Circular Move Mobility Model

The Circular Move Mobility Model is another form that is in between entity and group mobility models. Sensor nodes are placed in the environment at 8 deployment locations in a circular border and they move to the center of the circle with randomly selected speed and direction from pre-defined ranges, $[speedmin, speedmax]$ and $[0, \pi/10]$ respectively. Each movement in this model occurs in a constant time interval t, as in Random Walk Mobility model. However, nodes in this model are moving towards a smaller circular zone in the center of the area and this behavior forces the movement to be in groups; meaning closely deployed nodes will be neighbors with high probability.
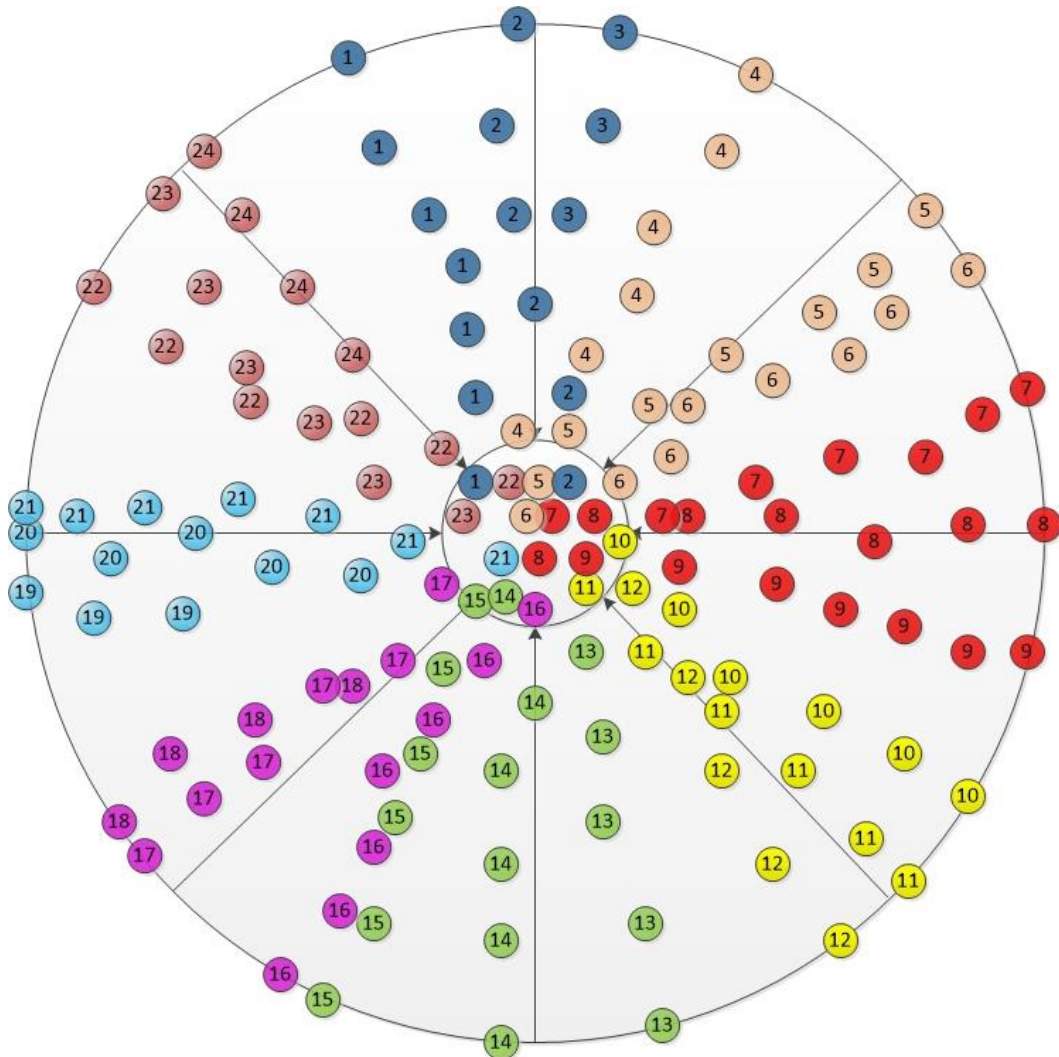
Figure 3 - Movement model of Circular Move Mobility model with sample sensor nodes

We depict a small sample movement model in Figure 3 using 24 sensor nodes deployed at 8 locations 3 nodes at a time. Directed lines show the movement direction and point to deployment locations on the border. We have assumed that there is a car moving on the border of the environment and stopping at these 8 pre-defined locations to deploy nodes. Since these nodes are deployed sequentially, they move to the center in spiral manner. Their movement pattern in the simulation environment is shown in Figure 4. As it can be observed from the movement pattern, nodes are covering the whole area with certain probability and they reach to every location on the environment while moving to the center of the area.
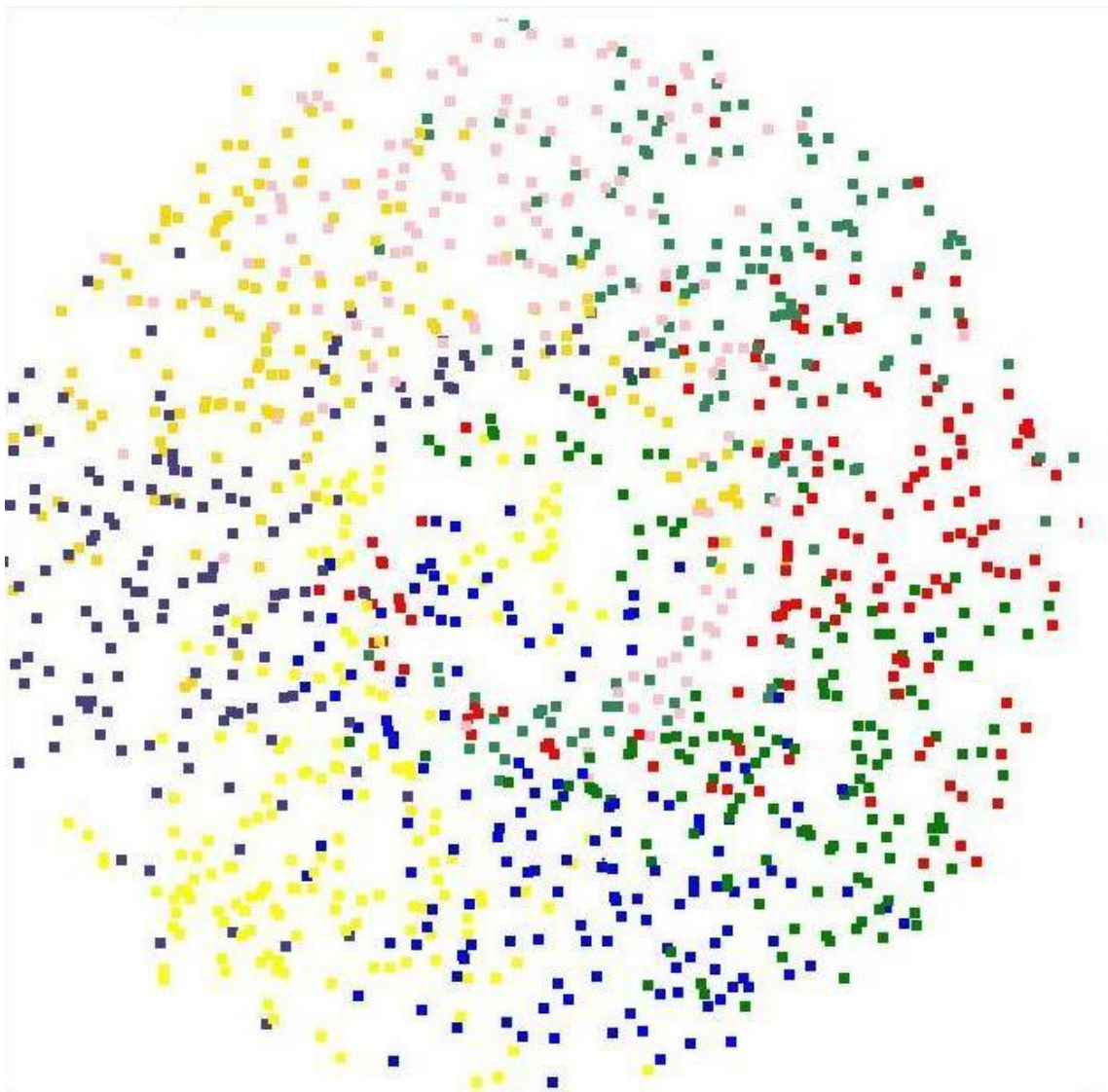
Figure 4 - Movement pattern of Circular Move Mobility model in simulations

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Besides combining entity and group mobility model features, Circular Move Mobility Model is an environmentally friendly mobility model. Sensor nodes end up at the circular area at the center of the environment when their batteries deplete. Therefore, in this mobility model, recycling dead nodes is much easier as compared to other models.

Chapter 3

Our Proposal: A Key Predistribution Scheme Based on Hash Graphs

This section describes our hash graph based key predistribution scheme proposal for mobile and multiphase wireless sensor networks. We provide the motivation behind this proposal; and we explain the key establishment phases along with an example to illustrate the procedure.

3. 1.   Overview

Sensor nodes have very limited amount of energy reserve that limits their lifetime to a small period of time. Typically, this restricted lifetime of sensor nodes is very short compared to the lifespan of the network. Hence, new sensor nodes need to be deployed to the network in some intervals called generations. WSNs with multiple generations are called multiphase WSNs in the literature. We propose a hash graph based key predistribution scheme (HaG) for multiphase WSNs that uses different key pools, called generation key pool, for each generation of the network. Nodes in HaG scheme are

deployed with a single generation key ring. Using this generation key ring, nodes can establish secure channels and communicate with their neighbor nodes for multiple generations.

In HaG scheme, key pool for a specific generation is constructed using key pools of previous generations. Two or more keys from previous generation are used to produce a key in a generation key pool. To some degree, nodes can use their key ring to generate keys in different key pools and use them for secure communication. Although there is a relation between key pools of different generations, this relation reduces in time in order to decrease attacker's ability to intercept certain portions of the network communication. This relation between different key pools allows nodes to be able to establish secure channels with the nodes that are deployed in different generations. This feature allows HaG scheme to have better connectivity between sensor nodes; details of which will be discussed in performance evaluation section.

The symbols and notations we use for our scheme in the rest of the thesis are listed in Table 2 below.

<div align="center">Table 2 - List of symbols used in our scheme</div>

Symbol	Definition
P	Key pool size
L_{max}	Maximum lifetime
KP^j	Key pool at generation j
KR_A^j	Key ring of node A at generation j
k_t^j	Key with index t at generation j
kg_t^j	Key group with index t at generation j
k_{AB}^j	Direct link key between nodes A and B for generation j
$h(\cdot)$	Secure hash function $h: \{0,1\}^* \to \{0,1\}^{160}$
$f(\cdot)$	Hash function $h: \{0,1\}^* \to \{0,1\}^{P/g}$
g	Number of key ring groups that are drawn from key pool
n	Number of key groups in the key ring of a node
m	Number of keys in the key ring of a node at the initial deployment time

In order to improve the resiliency against node capture attacks, we have employed the sensor node lifetime as an important parameter for our HaG scheme. Each sensor node has an upper bound of lifetime defined as L_{max} generations, which is referred as *maximum lifetime*. A node deployed at generation i will drain its battery before generation $i + L_{max}$ reaches. A node that is deployed at generation j should be able to establish a secure channel with the nodes that are deployed between $[j - L_{max}, j + L_{max}]$ generation periods, in an ideal world. However, it has very low probability to find two sensor nodes whose deployment generation difference is close to L_{max}. Therefore, key rings of nodes are distributed in groups considering the deployment generation difference. This restricts the use of a particular key for specific generations and therefore improves the resiliency against node capture attacks.

3. 2.   Motivation and Scalability of the Scheme

Main motivation behind our HaG scheme is to develop a key predistribution scheme for multiphase wireless sensor networks that has better resiliency against node capture attacks when compared to previously proposed schemes. Ergun et al. [3] have performed simulations to evaluate how much of the resiliency behavior of RoK scheme is attributable to backward and forward key pools. They have shown that backward key pool plays an important role in maintaining secure communication between sensor nodes. Their analysis also shows that the effect of the forward key pool to the security of the scheme remains constant after 5th generation. This means that most of the nodes deployed at the beginning of the network are still alive when the security provided by the forward key pool becomes steady. This observation is the base of our HaG scheme because we use one key pool of backward hashed keys in forward direction to deliver security in WSNs. Instead of using forward and backward hash chains, as in RoK scheme, we use one key pool and evolve it in hash graph manner that simulates the backward key pool behavior in itself. This form of key pool generation makes sure that our proposal includes both forward and backward secrecy features.

Furthermore, multiphase wireless sensor networks are deployed to environments in order to accomplish various tasks for a long period of time. Although network lifetime can be determined before starting the node deployment, this may not be the case for all

deployment scenarios. Therefore a key predistribution scheme should be able to adapt changes in the network and its lifetime. As we have mentioned before, RoK scheme uses one backward and one forward key pool. However, backward key pool of RoK scheme should be computed before starting the deployment phase and this makes it impossible to change the lifetime of the WSNs once it starts to operate. Therefore we can say that it is not possible to scale the WSNs lifetime if we are using RoK scheme. Conversely, HaG scheme starts functioning with one key pool and evolves its keys in time using an algorithm that we will be explaining in detail below. This feature makes it easy to scale the network lifetime and add more generations to the WSNs as desired. The last generation key pool of the proposed scheme can be evolved using the same algorithm and this new key pool can be used for the nodes that are to be deployed in new generations. Therefore, HaG scheme does not have a lifetime scalability problem.

3. 3.   Key Establishment Phases

There are three implementation procedures for our scheme: key pool generation, key ring predistribution and pairwise key establishment. The subsections below explain the details of these procedures. Figure 5 shows the generation key pools and depicts the key rings of two nodes. This figure is used in explaining the procedures and denoting the equations. We also give an example for key establishment phase using the nodes shown on Figure 5.

3.3.1.   Key Pool Generation

Key pool of HaG scheme is updated at each generation. Unlike RoK scheme, we use only one key pool for generations and evolve them with different algorithm. The initial key pool has P randomly generated keys. When the generation period ends, two consecutive keys are XORed and hashed with a secure hash function $h: \{0,1\}^* \rightarrow \{0,1\}^{160}$, such as SHA1 [14], to generate one key from key pool of the next generation.

Generation key pool of the first generation is depicted in Figure 5, as the first row. More precisely, initial key pool of the network at generation 0 is defined as follows:

$$KP^0 = \{k_1^0, k_2^0, k_3^0, k_4^0, k_5^0, \dots, k_{P-1}^0, k_P^0\} \tag{10}$$

where each k_i^0 value is randomly generated.

Key pool at generation j and $j+1$ is denoted as follows:

$$KP^j = \{k_1^j, k_2^j, k_3^j, \dots, k_P^j\} \tag{11}$$

$$KP^{j+1} = \{k_1^{j+1}, k_2^{j+1}, k_3^{j+1}, \dots, k_P^{j+1}\} \tag{12}$$

Keys in the generation $j+1$ are generated by just performing a simple hash operation over two keys from the previous generation j. The relation between keys at different generations can be defined as:

$$k_t^{j+1} = h\left(k_t^j \oplus k_{t+1}^j\right) \tag{13}$$

To reserve the key pool size P in every generation, k_P^{j+1} key is generated randomly and added to the end of KP^{j+1} key pool.

Generation key pools of the successive generations are shown in Figure 5 and they are marked with their generation number on left. Purpose of having some colored keys is explained in Section 3.3.3.

3.3.2. Key Ring Predistribution

In our scheme, we predistribute keys in groups of g keys from the generation key pool of size P. Each node has m keys that can be used to communicate with other nodes that are deployed to the environment at the same generation. Thus, nodes are loaded with $n = m/g$ different key groups from the key pool of their deployment generation. These key groups are selected using a pseudorandom function $f(\cdot)$ which does not produce consecutive numbers for the same node. For example, the first key group of the node A deployed at generation j is $f(id_A \parallel 1 \parallel j)$ which contains keys in $[f(id_A \parallel 1 \parallel j) \times g, f(id_A \parallel 1 \parallel j) \times (g+1)[$ interval.

More precisely, key ring of node A is constructed as:

$$KR_A^j = \{kg_t^j \mid t = f(id_A \parallel i \parallel j), i = 1,2,3,\dots,n\} \tag{14}$$

And one of these key groups can be defined as:

$$kg_t^j = \left\{ k_{t \times g}^{j+1}, k_{t \times g+1}^{j+1}, k_{t \times g+2}^{j+1}, \dots, k_{(t+1) \times g-1}^{j+1} \right\} \tag{15}$$

Distribution of keys in groups allows nodes to have better chances of communication with nodes deployed in the future generations. As shown in Figure 5, a node can only update its key ring for a limited number of generations. We also make sure that our pseudorandom function $f(\cdot)$ does not give two consecutive group numbers for the same node; because this will give the attacker the advantage to compromise keys for more generations, and eventually reduce the resiliency of the scheme faster. For the same reason, we suggest that the number of keys in groups, g value, should be determined close to $L_{max}/2$; based on the observations on age distribution of the nodes provided in RoK scheme [1].

One thing to note here is that a given node A can only update its key ring KR_A^j for the generation i between j and $j + g$. This situation is shown in Figure 3 for two nodes. Since he will have at most g keys in groups and the $f(\cdot)$ function does not give consecutive group numbers, node A cannot update its key ring KR_A^j beyond generation $j + g$. This means that the lifetime of the key ring possessed by the node is limited. Therefore, an attacker that captures a node will only be able to use its compromised keys for a very limited period of time. As we will see later in performance analysis section, this is an important feature of HaG scheme that makes it more resilient against node capture attacks.

By design, HaG scheme provides some security measures for the generation key pools. Security of the future generation key pool is provided by using two sequential keys to produce a key in the next generation. If an attacker captures a node, he will only be able to compromise keys for g generations. Security of past generation key pool is provided by the secure hash function $h(\cdot)$. An attacker is not able to recover any of the past keys even he captures all of the alive nodes in the network. These security precautions increase the resiliency of the HaG scheme against node capture attacks.
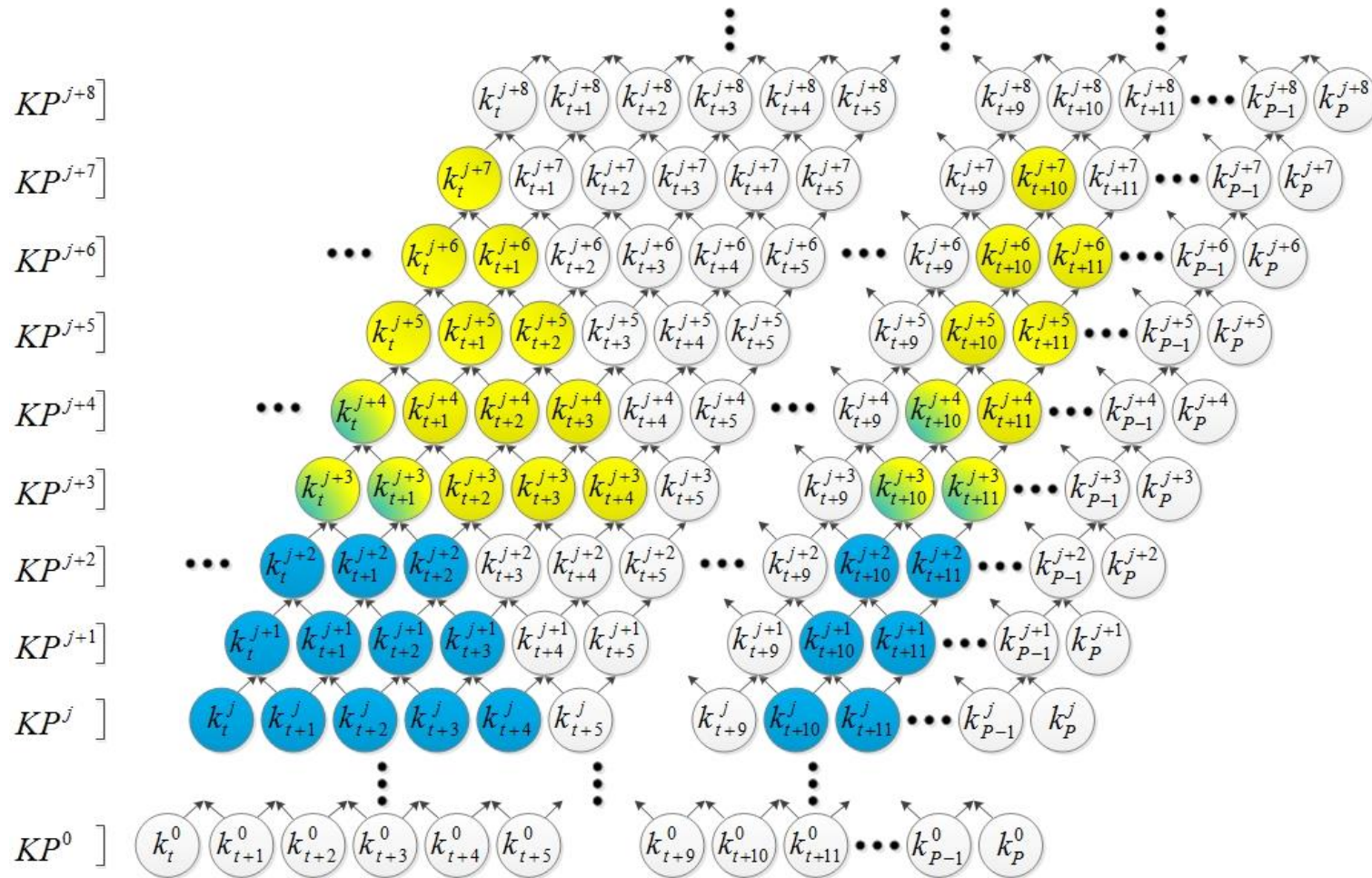
Figure 5 - Key pool generation and pairwise key establishment in our scheme

3.3.3. Pairwise Key Establishment

Nodes start pairwise key establishment phase right after being deployed to the environment. When a sensor node A, with node identifier id_A, is deployed to the network at generation j, it broadcast a message containing these values. Neighbor nodes can use this message to construct list of indexes in the key ring KR_A^j and using this key index list. Then using this list, they can check whether they have at least one common key or not.

If node A is deployed at generation j and node B is deployed at generation i where $i \leq j$, then they can find a common key in $[j, i + g[$ generation interval. If they find at least one common key, then they XOR all common keys and then hash the result to generate k_{AB} which is used to secure the communication between nodes A and B. Note that if A and B have the key indices $t_1, t_2, \ldots, t_z$ in common, then they both can compute the keys $\{k_\tau^\gamma | \tau = t_1, t_2, \ldots, t_z, \gamma = j, j + 1, \ldots, i + g - 1\}$ and use them for secure communication.

Node A and B can then compute their secret key for generation j as follows:

$$k_{AB}^j = h(k_{t_1}^j || k_{t_2}^j || k_{t_3}^j || \ldots || k_{t_z}^j) \tag{16}$$

The key k_{AB}^j can then be used to secure communication between sensor nodes A and B until the generation period j ends. When the generation period ends, nodes should immediately generate the keys of the succeeding generation and delete the keys from the past generation key pool. This improves the resiliency of the network deeply because nodes that are not yet captured by an attacker will not disclose as much key as they would, if they were to store the keys of the past generations.

3.3.4. Key Establishment Example

In this section, we provide an example for the pairwise key establishment protocol of HaG scheme. As seen in Figure 5, we have two nodes, A and B, that are deployed at generations j and $j + 3$ consecutively, with a maximum lifetime $L_{max} = 10$ and $g = G_w/2 = 5$. Node A is deployed with the blue colored keys and node B is deployed with the yellow colored keys in their initial deployment generation. More formally, key rings of these nodes are as follows:

$$KR_A^j = \left\{ ..., k_t^j, k_{t+1}^j, k_{t+2}^j, k_{t+3}^j, k_{t+4}^j, k_{t+10}^j, k_{t+11}^j, k_{t+12}^j, ... \right\}$$

$$KR_B^j = \left\{ ... k_t^{j+3}, k_{t+1}^{j+3}, k_{t+2}^{j+3}, k_{t+3}^{j+3}, k_{t+4}^{j+3}, k_{t+10}^{j+3}, k_{t+11}^{j+3}, k_{t+12}^{j+3}, ... \right\}$$

These key rings allow node A and B to communicate in $j + 3$ and $j + 4$ generations only, using the set of $\left\{ k_t^{j+3}, k_{t+1}^{j+3}, k_{t+10}^{j+3}, k_{t+11}^{j+3}, k_t^{j+4}, k_{t+10}^{j+4} \right\}$ keys. They cannot communicate in any other generation using these two key groups but this is just for illustration purposes. Formally, secret key between node A and B in generations $j + 3$ and $j + 4$ can be defined as:

$$k_{AB}^{j+3} = h\left(k_t^{j+3} \oplus k_{t+1}^{j+3} \oplus k_{t+10}^{j+3} \oplus k_{t+11}^{j+3} \right) \tag{17}$$

$$k_{AB}^{j+3} = h\left(k_t^{j+4} \oplus k_{t+10}^{j+4} \right) \tag{18}$$

When the generation $j + 4$ arrives, node A and B update their key rings. They should also immediately erase keys from the generation $j + 3$, in order to increase the resiliency of the network. One other thing to note here is that node A can only communicate with the nodes deployed between generation j and $j + 5$. Similarly, node B can only communicate with the nodes deployed between generation $j + 3$ and $j + 8$. This limitation is because of the number of keys in groups, g value, and its relation is described above in Key Ring Predistribution section.

Chapter 4

Performance Evaluation of HaG Scheme

Performance analysis of the proposed HaG scheme is done by carrying out several simulations. We have considered different scenarios and mobility models in these simulations and compared our results with RoK scheme. We first describe the attack model and formulate the resiliency metrics. Then we explain the simulation setup and discuss performance results obtained.

4. 1.   Attack Model and Resiliency Metrics Formulation

In this section, we are going to define attack models to WSNs and formulate our resiliency metrics. We use node capture attacks as the main threat in WSNs as in other studies in the literature such as [1-3, 5-10].

In the attack model, we assume that there is an attacker who has the ability to capture nodes at random locations from the environment. The rate at which this attacker captures nodes is defined as a system parameter and we have clearly indicated these

values in our simulations. When a node is captured by the attacker, all the keys possessed by that node are recorded in the memory of the attacker for further use in eavesdropping communications between other nodes. Because same keys can be reused during the course of the network by several nodes, attacker can use these captured keys to compromise the secure links between nodes that are not yet captured. Attacker uses captured keys and builds a hash graph of generation key pools as he continues to capture nodes. As we described before, our aim is to reduce the effect of node capture attacks on the security of the links between these unaware nodes and subsequently increase the resiliency against node capture attacks.

We considered two different types of attackers: the eager and the temporary attackers. Both of these attackers start capturing nodes from 5th generation of the network. An eager attacker continuously compromise nodes at constant rate until the end of the network lifetime. This rate is defined as a system parameter and given in simulation results. Conversely, temporary attacker compromises nodes till 14th generation in our simulations. We have selected these generation parameters to be compatible with the simulations in RoK scheme [1].

We then calculated, at each time interval, the number of compromised links in order to evaluate the resiliency performance against node capture attacks. This is the number of links that are secured using keys captured by the attacker; i.e. compromised links that can be eavesdropped. As it is clear from the description, if this number is low, then the employed key predistribution scheme is more resilient.

In our simulations, we have used two resiliency metrics for evaluation: active resiliency and total resiliency. We have evaluated these metrics for both schemes, RoK and HaG, by performing simulation and discussed the results in Section 4.5.

4.1.1. Active Resiliency

Active Resiliency is the resiliency of currently active links against node capture attack. A communication link is said to be *active* when both nodes at its ends are still alive and they both continue collecting information from the environment. An attacker

that holds the encryption key of an active communication link can decrypt all the messages between communicating nodes. Active resiliency is measured as *active compromised link ratio*; defined as the ratio of the number of indirectly compromised active communication links over the total number of active communication links. Active resiliency performance of the network is better when this ratio is lower.

4.1.2. Total Resiliency

Total Resiliency is the resiliency of all links (established by active and dead nodes) against node capture attacks. It is measured as total compromised link ratio, which is the ratio of the number of indirectly compromised active and dead communication links that are formed from the beginning of the network over the total number of communication links that are formed from the beginning of the network. If the total compromised links ratio is lower, total resiliency performance of the network is better. This metric is important because attacker can record all the information transferred over the network even if he does not have the ability to decrypt the message. Later he can use all the keys that he gathered from the captured nodes and go over these messages to decrypt them. Therefore, Total Resiliency of the scheme is as important as the Active Resiliency in evaluating a key predistribution scheme.

Although these metrics are called active and total resiliency, they both have an inverse relation to the active and total compromised links ratio. When these ratios are low, then the network's resiliency is high. Therefore, this inverse relation should be kept in mind while evaluating the performance results.

4.2. Analytical Formulations

In this section, we describe analytical formulations o HaG performance metrics. In related literature, such as Basic [6], RoK [1] and RGM [2-3] schemes, performance metrics are formulated using some set theoretic rules and expressions. We also follow the same techniques in our formulations. We give formulations for both local connectivity and resiliency metric of HaG scheme.

We first formulate the key sharing probability of two neighboring nodes that are deployed at the same generation and define it as p_{sg}. As we have described before, nodes will get their key rings from the same key pool if they are being deployed at the same generation. Assuming that the probability of sharing at least i keys is defined as p_i, we formulate this as:

$$p_i = \frac{\binom{P}{i}\binom{P-i}{2(m-i)}\binom{2(m-i)}{m-i}}{\binom{P}{m}^2} \tag{17}$$

where m is the key ring size and P is the key pool size.

Therefore, the probability that two nodes deployed at the same generation share at least one key is defined as $1 - p_0$, which is:

$$p_{sg} = 1 - \frac{\binom{P}{2m}\binom{2m}{m}}{\binom{P}{m}^2} \tag{17}$$

Then we formulate the probability that neighboring nodes share at least one key when they are deployed at different generations and define it as p_{dg}. Using a set of m keys, a node can generate m/g keys in its future generations. Because nodes will update their key rings at each generation change and their keys will be deployed in groups of g keys, they will at most be able to generate m/g keys in their future generations. This is also dependent on the lifetime of the node, which will be described later. Therefore, probability formulation for the nodes deployed at different generations is:

$$p_{dg} = 1 - \frac{\binom{P}{m+m/g}\binom{m+m/g}{m}}{\binom{P}{m}\binom{P}{m/g}} \tag{18}$$

Considering these two equations, we need to find a threshold value for the connectivity of the network. We know that dead nodes are being replaced with new ones in the network when the generation period changes. Observing Equation 17 and 18, we can see that p_{sg} has m amount of effect in the total probability and p_{dg} has g

amount of effect on the probability. This will conclude that the probability of sharing at least one key is calculated as:

$$p_{connect} = p_{sg} + p_{dg} - p_{sg} \times p_{dg} \tag{19}$$

In Equation 19, nothing is dependent on the node density. The effect of node density is formulated in other schemes and we have employed their method for our calculations.

Our resiliency calculation consider the probability that a link is compromised when a given set of nodes are captured by the attacker. However, gradual changes at the round level cannot be observed due to approximations and randomness of the proposed scheme. We have performed extensive simulations to provide resiliency analysis of the proposed scheme, but we believe that providing an approximate analytical formulation is supportive.

Assuming that the average number of captured nodes at a given time is x, we know that the probability that a given key is not yet compromised is $\left(1 - \frac{m}{P}\right)^x$. If a given link is secured by q keys, then the probability that this link is compromised is defined as $\left(1 - \left(1 - \frac{m}{P}\right)^x\right)^q$. Therefore, the probability that an active link is compromised at generation j is defined as follows:

$$p_r \sim \sum_{i=1}^{m} \left(1 - \left(1 - \frac{m}{P}\right)^{x \cdot E[Z]} - \left(1 - \frac{m + \frac{m}{g}}{P}\right)^{x \cdot E[Z]} \right) p_i \tag{20}$$

The $E[Z]$ in this calculation uses g as the upper limit instead of the maximum lifetime value L_{max}. Therefore, the expected value of Z can be defined as:

$$E[Z] = \sum_{j=0}^{g} j \cdot P\{Z = j\} \tag{21}$$

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In Equation 20, nothing is dependent on the deployment generation because it will make the formulations much harder to define. We have left the final form to be independent of the deployment generation and therefore the results of these formulations will be constant. However, changes on the resiliency metric will be observable. We now give the analyses on simulations and then compare it with the analytical formulation results.

4.3.   Simulation Setup

We perform several simulations and compare our scheme with RoK scheme. We have used C# programming language to implement the simulations and run them on Microsoft Windows 7 operating system environment.

In these simulations, we set the key pool size to 10,000 keys for both schemes. We place sensor nodes to the environment in totally random manner to have more realistic simulations. We use 1,000 sensors on $400m \times 400m$ square environment for simulations with Random Walk Mobility and Reference Point Group Mobility models. In simulations where Circular Move Mobility model is used, average number of nodes is around 1,200 and diameter of the environment is set to $400m$. Since we are deploying 25 nodes per round, number of sensor nodes in the environment fluctuates when we use Circular Move Mobility model. Communication range for nodes is set to 40m in both of these simulation environments. L_{max} is set to 10 and sensor nodes have a random lifetime that is determined using a Normal distribution function with mean $L_{max}/2$ and standard deviation $L_{max}/6$. As explained before, g value is set to be 6 which is close to $L_{max}/2$. We have also assumed that each generation consists of 10 smaller time units called rounds. Dead nodes are replaced with new randomly placed nodes at the beginning of each generation.

Attack model that we have employed to evaluate the performance of the proposed scheme is described in Section 4. 1. above. Attacker's capture rate is selected as one, three and five nodes per round.

We run the simulations for 30 generations. Also, all of our simulations are run for 25 times and we report their average values for the sake of smoothness in the results.

4.4. Network Connectivity

We perform Global Connectivity and Local Connectivity analyses on both HaG and RoK schemes and compare their results using different mobility models.

We base our analyses on the Local Connectivity of the network and select key ring sizes according to Local Connectivity metric. For that reason, simulations on connectivity analysis of RoK and HaG schemes are done using key ring sizes of 200, 220 and 250 keys when nodes are moved using Random Walk Mobility and Reference Point Group Mobility models. For Circular Move Mobility model, we perform our simulations using 160, 205 and 265 keys.

Global Connectivity of the network is the ratio of the largest key sharing graph over the size of the network. This metric is useful in understanding the overall connectivity of the network. With the specified key ring sizes, both RoK and our scheme have 100% Global Connectivity using Random Walk Mobility and Reference Point Group Mobility models. Therefore, we do not show the Global Connectivity performance of RoK and HaG scheme using these mobility models. However, when we use Circular Move Mobility model, then the Global Connectivity of HaG scheme becomes around 95%, whereas Global Connectivity of HaG scheme is around 98%. We compare Global Connectivity of HaG and RoK scheme in Figure 6.

The difference between Global Connectivity results of RoK and HaG schemes is caused by the key ring size difference. In order to have same Local Connectivity value, we have selected the key ring sizes as 205 and 265 for HaG and RoK schemes respectively. But using lower number of keys in HaG ended up decreasing the Global Connectivity value as well. Besides, as seen in Figure 4, high density of the sensor nodes in the environment also affects the Global Connectivity results. Since we do not replace the dead nodes in the network, the graphs are a bit rugged in the Circular Move Mobility model.
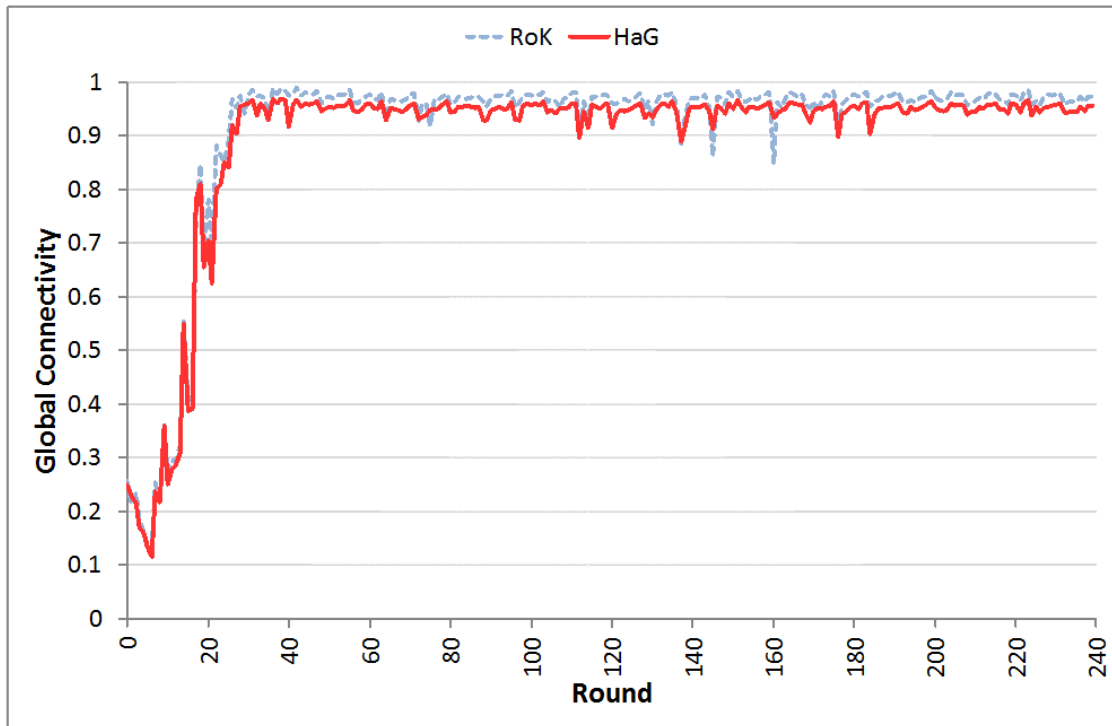
Figure 6 - Global Connectivity of RoK and HaG scheme using Circular Move Mobility model (with same Local Connectivity)

Local Connectivity is the probability that any two neighbor sensor nodes share at least one common key in their ring. This metric is especially important because it shows the probability of creating secure links between neighboring nodes. We have observed that using either Random Walk Mobility model or Reference Point Group Mobility model do not affect the Local Connectivity performance. Therefore, we treat them equally and show their performance in the same figure. Figure 7 shows the Local Connectivity values for both RoK and HaG schemes using 200, 220 and 250 keys as key ring sizes. As seen from this figure, nodes in both schemes have 0.8 Local Connectivity value when using 220 keys for HaG scheme and 250 keys for RoK scheme. For a WSN, 80% Local Connectivity is sufficient for covering most of the network. Figure 7 also shows that for the same key ring sizes, Local Connectivity performance of HaG scheme is around 10% better than the RoK scheme.

Similarly, simulations are performed to evaluate the Local Connectivity performance of HaG and RoK scheme when Circular Move Mobility model is used. In this simulation, we employ different key ring sizes and came up with a point where Local Connectivity value is around 90%. Local Connectivity performance using Circular Move Mobility model is presented using 160, 205 and 265 keys as shown in Figure 8. Local Connectivity performance of HaG scheme is around 10% better than the performance of RoK scheme, when the key ring sizes are the same.
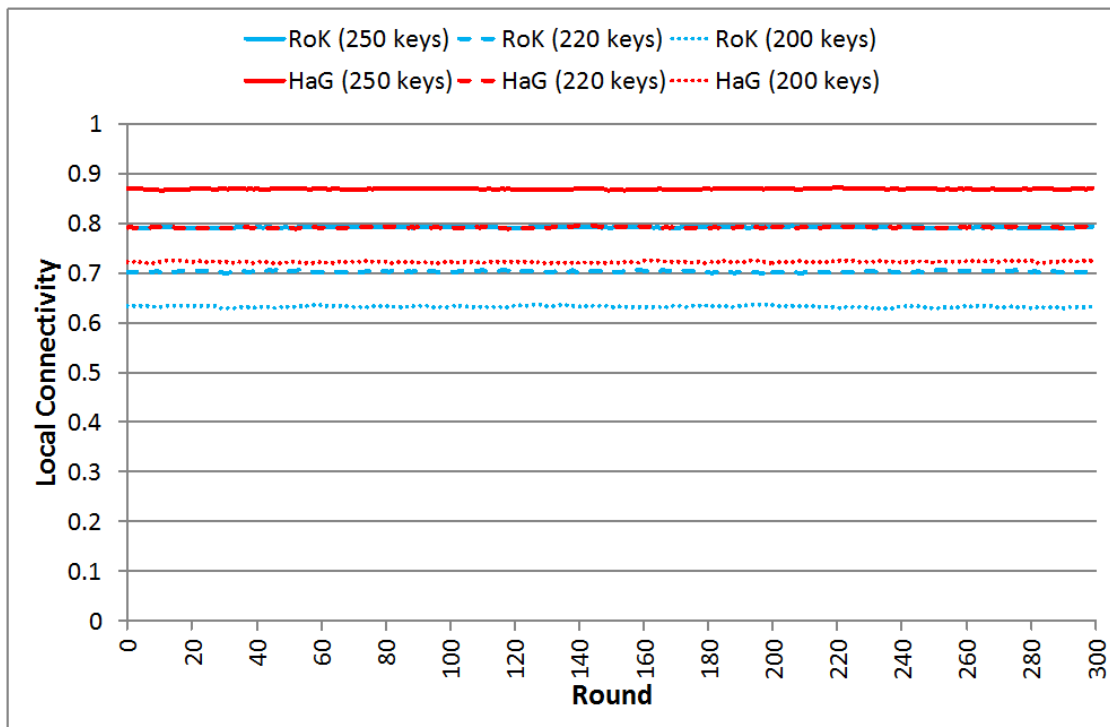

Figure 7 - Local Connectivity of RoK and HaG scheme using Random Walk Mobility or Reference Point Group Mobility model
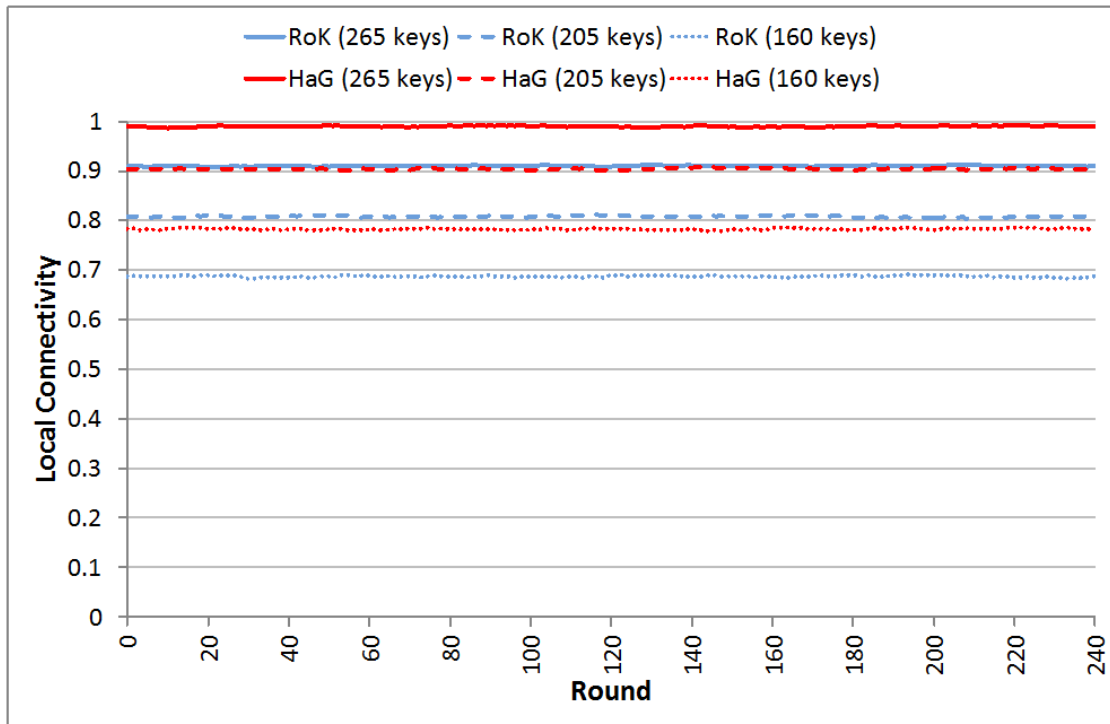
Figure 8 - Local Connectivity of RoK and HaG scheme using Circular Move Mobility model

Since Random Walk Mobility and Reference Point Group Mobility models have the same Local and Global Connectivity performance, we continue to use Random Walk Mobility together with Circular Move Mobility model and drop Reference Point Group Mobility Model in our further evaluations.

4.5. Resiliency against Node Capture Attacks

Considering the Local Connectivity as the basis of our measures, we perform the resiliency analyses using Random Walk Mobility and Circular Move Mobility models. In our simulations, attacker actively captures 1, 3 and 5 nodes per round randomly and compromises all of the keys available in their memory.

4.5.1. Resiliency Performance using Random Walk Mobility

In Random Walk Mobility model, key ring size is set to 220 for HaG scheme and 250 for RoK scheme. These key ring sizes are selected according to the Local Connectivity performances, which is same for both schemes and around 0.8 as seen in Figure 7. Figure 9 and 10 show the Active Resiliency and Total Resiliency comparison of RoK scheme and our HaG scheme using actual and total compromised links ratios; the lower the compromised links ratio, the better.

Active compromised links ratio is calculated using nodes that are currently alive and has some keys compromised because attacker has captured some other nodes that are able to communicate. As it can be seen in Figure 9, active compromised links ratio reaches its highest value in around 10th generation when most of the nodes that are deployed at the 5th generation are still alive. After 10th generation, nodes that are deployed at 5th generation start to die in accordance with their lifetime determined using normal distribution.
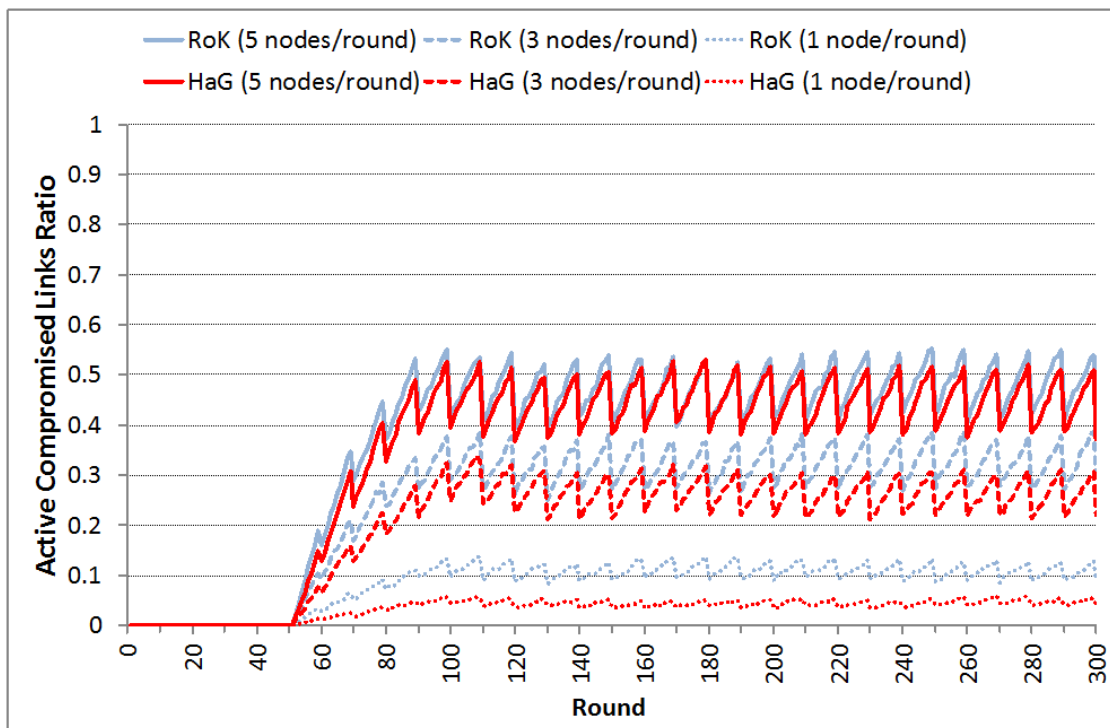

Figure 9 - Active Compromised Links Ratio of RoK and HaG schemes with an eager attacker having capture rates of 1, 3 and 5 nodes per round (using Random Walk Mobility or Reference Point Group Mobility model)

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Our results show that our scheme performs nearly 50% better when the attack rate is low, i.e. attacker captures one node per round. Although increasing attack rate negatively affects the performance of our scheme, our results are still better than RoK scheme.

Total compromised links ratio is calculated by considering all dead (i.e. captured) or alive links that are established over the course of the network. Our simulations have shown that total resiliency of HaG scheme also outperforms the RoK scheme as it can be seen in Figure 10. Similar to the active resiliency, HaG scheme has nearly 50% better results when the attack rate is low. When the attack rate increases, HaG scheme still has lower total compromised links ratio compared to the RoK scheme.
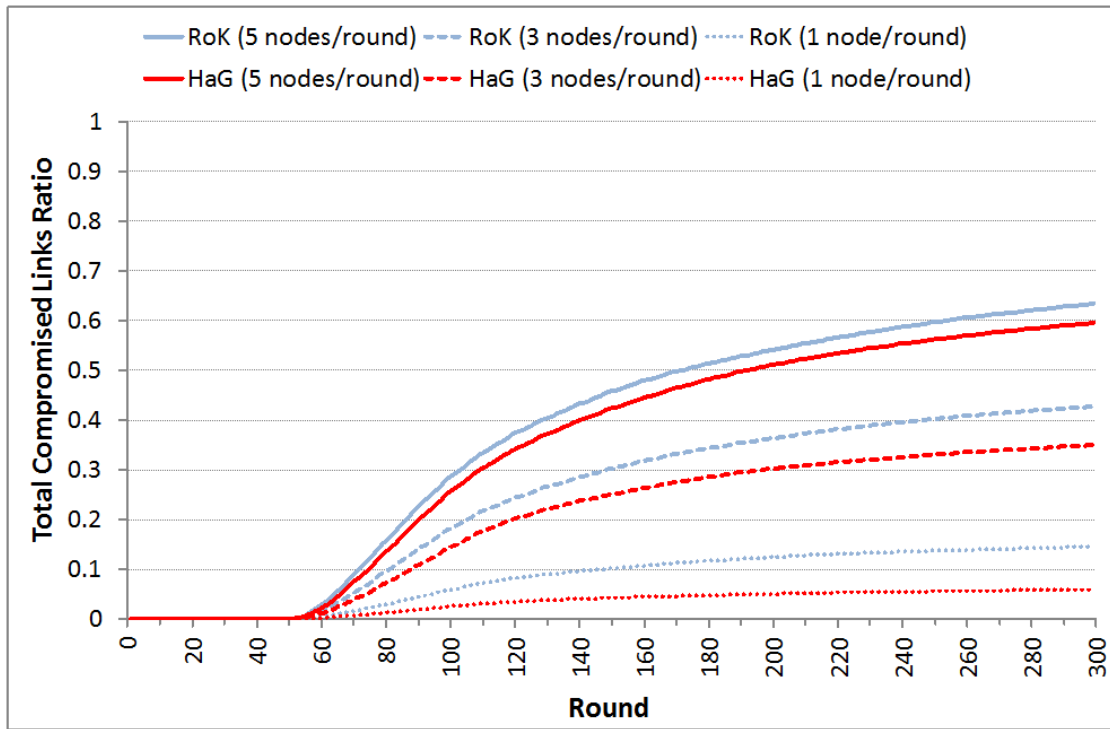

Figure 10 - Total Compromised Links Ratio of RoK and HaG schemes with an eager attacker having capture rates of 1, 3 and 5 nodes per round (using Random Walk Mobility or Reference Point Group Mobility model)

Figure 11 shows the active compromised links ratio of HaG and RoK schemes in case of a temporary attacker starting its activity in generation 5 and ending in generation 14. The attacker starts capturing 1, 3 and 5 nodes per round and the compromised links ratio

increases to its highest value. After the attack stops, both networks start to heal, i.e. recover their initial state and eliminate the effects of the attack on the key pools. As it can be seen from the Figure 11, networks completely heal at almost the same time. However, our HaG scheme's healing acceleration is higher than RoK; thus, HaG's healing effect starts to improve resiliency at earlier generations as compared to RoK after the attack stops.
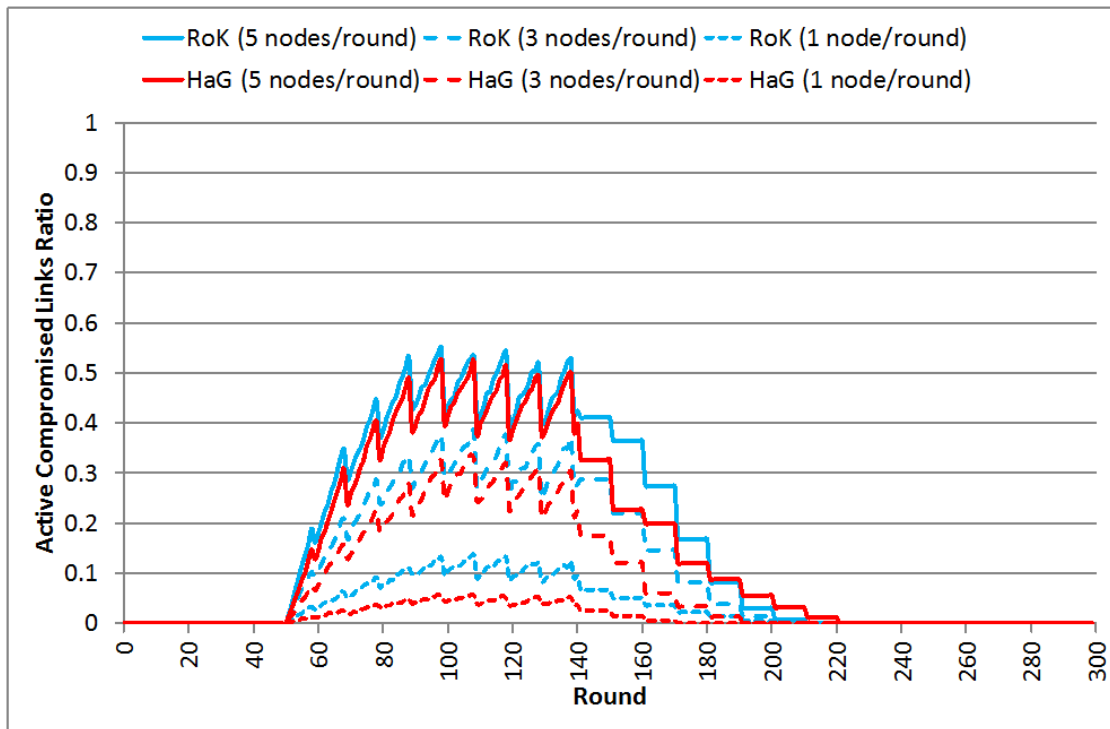

Figure 11 - Active Compromised Links Ratio of RoK and HaG schemes with a temporary attacker having capture rates of 1, 3 and 5 nodes per round (using Random Walk Mobility or Reference Point Group Mobility model)

4.5.2. Resiliency Performance using Circular Move Mobility

When Circular Move Mobility model is used, key ring sizes are selected as 205 and 265 for HaG and RoK schemes respectively. Using these key ring sizes, Local Connectivity performance of HaG and RoK scheme is around 0.9 as seen in Figure 8.

Active compromised links ratio comparison of HaG and RoK scheme using Circular Move Mobility model in case of eager and temporary attackers is shown in Figure 12

and 13, respectively. Simulation results show that our scheme performs nearly 40% better when the attack rate is low, i.e. attacker captures one node per round. However, the effect of increasing attack rate is not that sharp when compared to the performance of other mobility models. In fact, there is a considerable amount of gap between the resiliency performances of HaG and RoK even if the attack rate is increased to five nodes per round. The reason behind this difference is the difference between key ring sizes. We use the same key pool size for both schemes but HaG has considerable amount of reduced key ring size. However, they both have the same Local Connectivity values in the analysis as mentioned above.
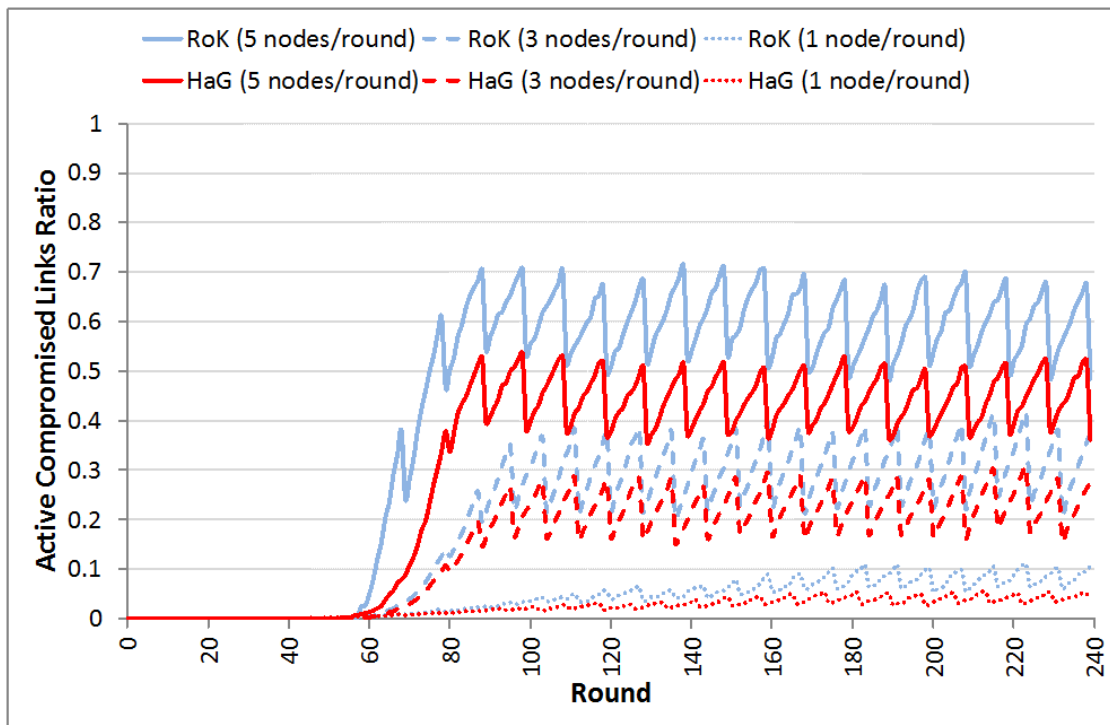

Figure 12 - Active Compromised Links Ratio of RoK and HaG schemes with an eager attacker having capture rates of 1, 3 and 5 nodes per round (using Circular Move Mobility model)
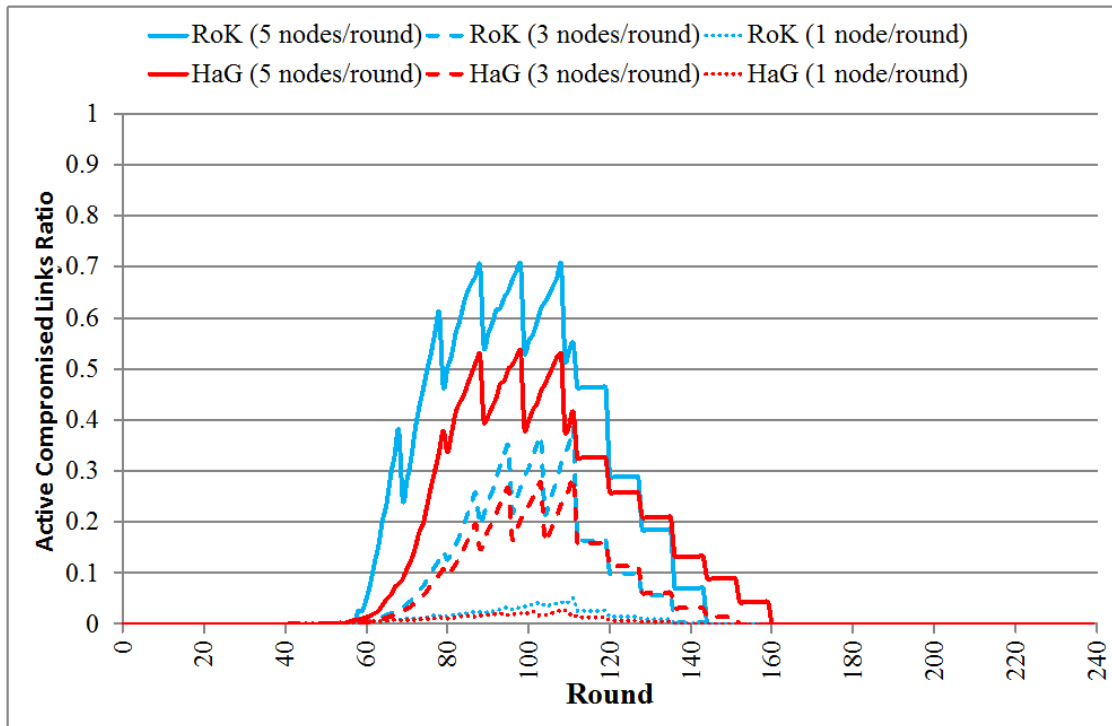
Figure 13 - Active Compromised Links Ratio of RoK and HaG schemes with a temporary attacker having capture rates of 1, 3 and 5 nodes per round (using Circular Move Mobility model)

Total compromised links ratio comparison of HaG and RoK scheme using Circular Move Mobility model is shown in Figure 14. Our simulations show that total resiliency of HaG scheme also outperforms the RoK scheme. Similar to the active resiliency, HaG scheme performs nearly 40% better when the attack rate is low. When the attack rate increases, HaG scheme still has lower total compromised links ratio compared to the RoK scheme and the difference between these schemes is much clearer than that of Random Walk Mobility case.

4.6. Comparison of Analytical Formulations and Simulation Performance

In this section, we compare the simulation results of HaG scheme with the result of the corresponding analytical formulations. The reason of making such comparison is to validate our simulations. As sample cases from connectivity and resiliency analyses, we have considered local connectivity and active compromised links ratio metrics.
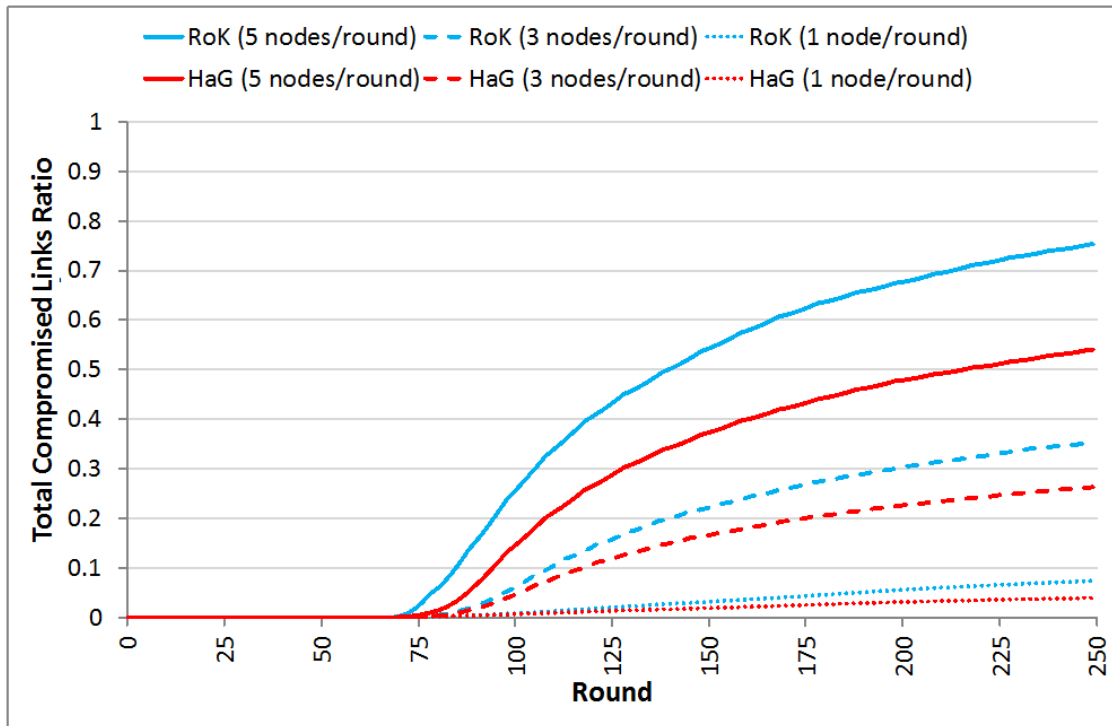
Figure 14 - Total Compromised Links Ratio of RoK and HaG schemes with a temporary attacker having capture rates of 1, 3 and 5 nodes per round (using Circular Move Mobility model)

Figure 15 and 16 show the comparison of simulation results of local connectivity with the analytical formulation given in Equation 19. As seen in these figures, analytical results and the corresponding simulation results are the same. We have used two different graphs to show the local connectivity comparison because node densities in different mobility models are not the same. Essentially, we have two different environments for Random Walk Mobility model and Circular Move Mobility model. As we discuss in analytical formulations section, this difference in node densities affects the local connectivity performance.
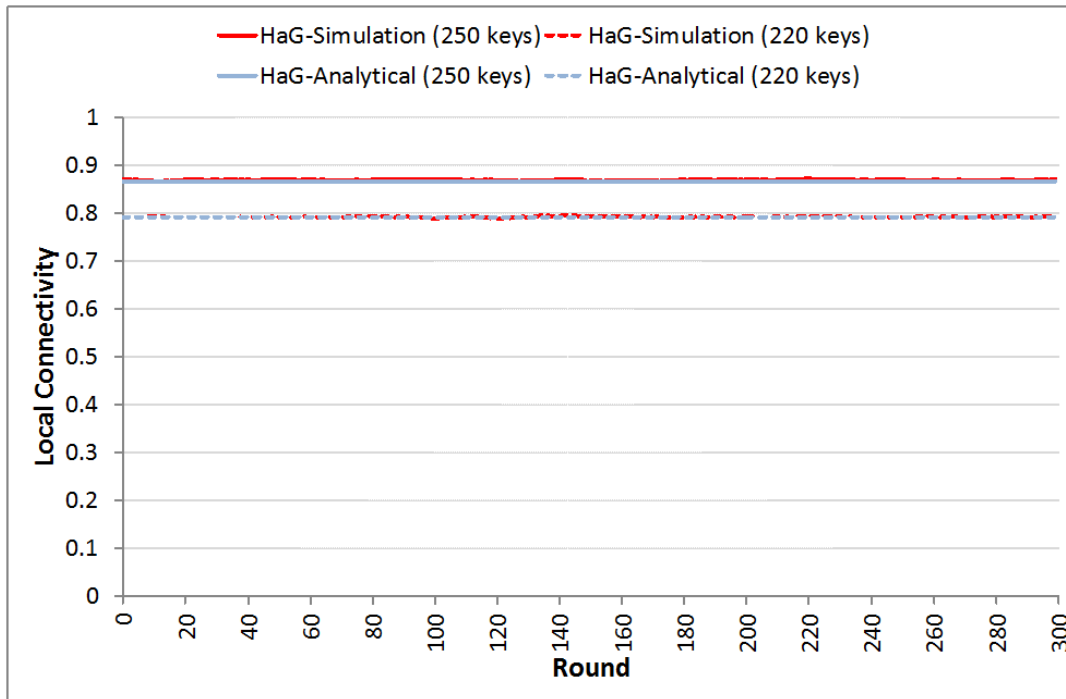
45

Figure 15 - Local Connectivity comparison of HaG Scheme: simulation vs. analytical (using Random Walk Mobility Model or Reference Point Group Mobility model).
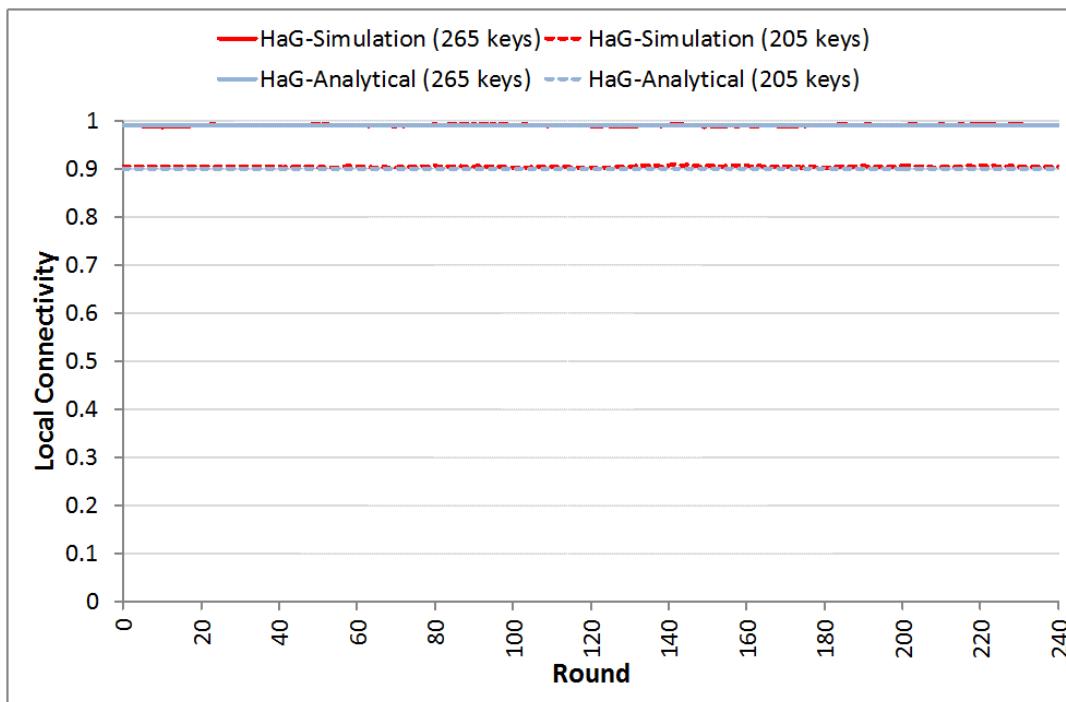

Figure 16 - Local Connectivity comparison of HaG Scheme: simulation vs. analytical (using Circular Move Mobility Model).

Figure 17 and 18 show the comparison of simulation results of active compromised links ratio with the analytical formulation given in Equation 14. As seen in these figures, analytical results go over a line that averages the corresponding simulation results. The reason of having a straight line and not having zigzags in the analytical case is that we do not consider rounds in our formulations.

These observations clearly verify our simulation results and the correctness of our simulation environment.

Figure 17 - Active Compromised Links Ratio comparison of HaG Scheme with an eager attacker having capture rates of 3 and 5 nodes per round: simulation vs. analytical (using Random Walk Mobility Model or Reference Point Group Mobility Model).
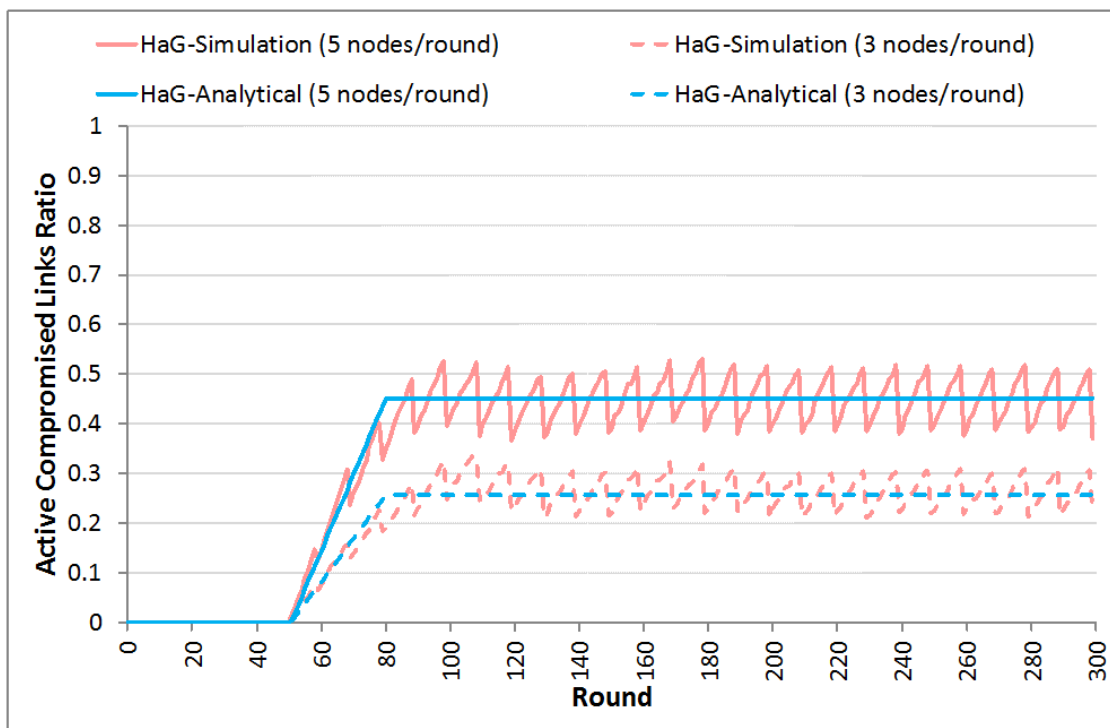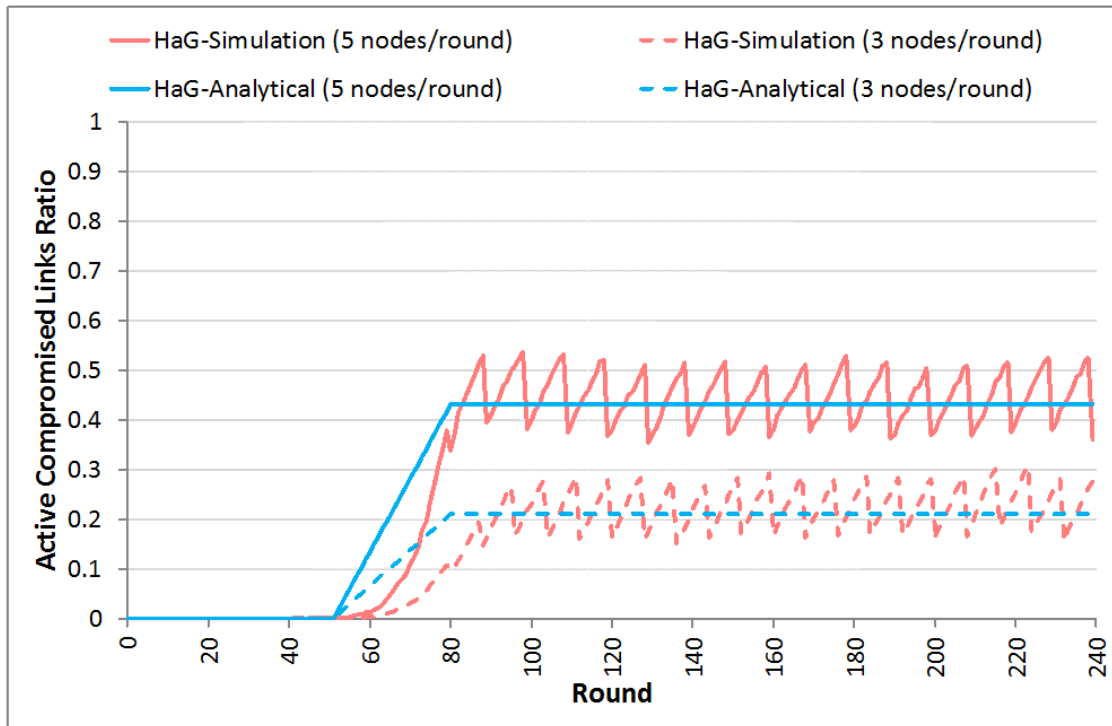
Figure 18 - Active Compromised Links Ratio comparison of HaG Scheme with an eager attacker having capture rates of 3 and 5 nodes per round: simulation vs. analytical (using Circular Move Mobility Model).

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Chapter 6

Conclusions and Future Work

In this thesis, we propose a new key predistribution scheme that is designed for multiphase wireless sensor networks. Our scheme starts with an initial set of random key pool that evolves over time, in a graph fashion, to generate key pools for the subsequent generations. Sensors deployed at different generations start with a key ring that is randomly selected from the key pool of their deployment generation in groups. Deploying keys in groups increases connectivity and decreases resiliency. An attacker capturing a node can only compromise keys for generations bounded by the key group size.

We have performed simulations on different mobility models and discussed their performance results. Our simulations have shown that after fixing the local connectivity value to the same value for both our scheme and RoK scheme using both Random Walk and Circular Move mobility model, resiliency performance of our scheme is 50% better when the attack rate is small. When the attack rate increases, our scheme still performs better as compared to RoK scheme but relative benefit decrease to %10. Our analysis has

shown that Circular Move mobility model gives better results for our proposal than Random Walk Mobility and Reference Point Group Mobility models.

Our broad analyses on both active and total resiliency metrics have shown that our HaG scheme has better resiliency performance than the RoK scheme at all capture rates. HaG scheme increases the resiliency performance by 50% when the attack rate is low. When the attack rate increases; resiliency performance increases by 10% and 30% for Random Walk Mobility and Circular Move Mobility models respectively.

Finally, we discuss some future works that can be done on top of HaG scheme in order to further improve resiliency performance. We have simply used two consecutive keys to update the generation key pools in HaG, but one could use multiple keys or even different methods to update the key pools. Using multiple keys to update a key to the next generation would increase resiliency against node capture attacks. Instead of using just one hash graph to distribute key rings to sensor nodes, one could use multiple hash graphs and increase the resiliency. Similarly, one could use one forward and one backward hash graph and update them as in RoK scheme. This would decrease the connectivity of the network drastically, but its effect on the resiliency is worth analyzing. For that matter, usage of multiple forward and backward hash graphs may as well have better resiliency performance.

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