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계층적 무선 센서 네트워크에서의 키관리 메커니즘

(On the Security of Hierarchical Wireless Sensor Networks)

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요 약

본 논문에서는 계층적 무선 센서 네트워크를 위한 그룹기반 보안 메커니즘을 제안한다. 이를 위해 세 가지 형태의 노드(베이스 스테이션, 그룹 관리 노드, 센서 노드)로 구성된 3계층 센서네트워크에서 안전한 라우팅을 위한 구조를 설계한다. 그룹기반 배치는 가우시안(Gaussian) 분산을 이용하여 수행되며, 제안된 모델을 사용해 85% 이상의 네트워크 연결이 가능하다. 이미 보안 기능을 공유하고 있는 작은 그룹들은 안전한 그룹을 형성하고, 그룹 관리 노드들은 전체 네트워크의 백본을 형성한다. 본 논문의 보안 메커니즘은 배치된 센서 그룹에서 수집된 데이터를 처리하기 위해 제안되었으며, 관리노드에 의해 수집된 센싱 데이터는 다른 관리노드를 거쳐 베이스 스테이션에 전달된다. 제안된 메커니즘은 경량화 되었고, 노드 캡처 공격에 강력하게 대응할 수 있으며 분석 자료와 시뮬레이션을 결과를 통해 이러한 특징을 확인할 수 있다. 또한, 분석 자료를 통해 그룹 관리노드와 센서 노드가 조밀하게 배치되었을 때 안전성이 크게 향상됨을 알 수 있다.

Abstract

We propose a group-based security scheme for hierarchical wireless sensor networks. We model the network for secure routing with 3-tier sensor network comprised of three types of nodes: Base Station, Group Dominator and ordinary Sensor Nodes. Group-based deployment is performed using Gaussian (normal) distribution and show that more than 85% network connectivity can be achieved with the proposed model. The small groups with pre-shared secrets form the secure groups where group dominators form the backbone of the entire network. The scheme is devised for dealing with sensory data aggregated by groups of collocated sensors; i.e., local sensed data are collected by the dominating nodes and sent an aggregated packet to the base station via other group dominators. The scheme is shown to be light-weight, and it offers a stronger defense against node capture attacks. Analysis and simulation results are presented to defend our proposal. Analysis shows that robustness can significantly be improved by increasing the deployment density using both the dominating and/or ordinary sensor nodes.

Keywords : Hierarchical, Security, Node Capture Attacks, Robustness, Wireless Sensor Networks.

I. Introduction

Wireless sensor networks (WSNs) are envisioned to be economic solutions to many applications as forest fire detection, battlefield surveillance, disaster management, homeland security operations, border control and so on [5, 6]. Generally, each sensor node in the network acts as an information source, sensing and reporting data from the environment for a given task. The low-cost sensor nodes forward the relevant data to a querying sink/base station (BS). However, reporting sensing data is often unnecessary as in many cases sensor nodes in an area detect the common phenomena. So there is a high redundancy in sensed data. Nevertheless, it is very inefficient for every single sensor to report their data back because every data packet traverses many hops to reach

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BSand nodes are stringent in resources (e.g., memory, communication, computation and battery).

Recently many data aggregation protocols[1~4] have been proposed to eliminate the data redundancy in sensor data of the network, hence reducing the communication cost and energy expenditure in data collection. During a typical data aggregation process, sensor nodes are organized into a tree hierarchy rooted at a BS. The non-leaf nodes act as aggregators, fusing the data collected from their child nodes before forwarding the results towards the BS. In this way, data are processed and fused at each hop on the way to the BS, and communication overhead can be largely reduced. In [9], an improved performance of the existing key-pre-distribution techniques has been presented using the locality of group deployment. The proposed framework in [9] does not require the sensors' expected locations for key-pre-distribution. This paper presents a group-based deployment approach similar to the scheme in [9] to model the network. However, our approach differs from [9] as our primary goal is to deal with sensed information aggregated by groups of collocated sensors and to show the tolerance against node capture attacks. We show that, unlike the tree-based topology, group-based deployment may also result in efficient and secure data aggregation. Topology consists of heterogeneous entities: Base Station (BS), Group Dominator (GD), and ordinary Sensor Node (SN). To preserve the efficiency, our scheme performs data aggregation in each logical group and generates one aggregate from each group. After the BS has collected all the group aggregates, it then checks the validity of the carried MACs (Message Authentication Codes) in the reports and discards the forged report if any. Our analysis and simulation results show the scheme's tolerance against increasing number of node compromise.

The rest of the paper is organized as follows. Section II presents existing works on this area. In Section III we model the distributed sensor network topology and describe our security aware data aggregation scheme in details. Security analysis and simulation results are presented in Section IV. We conclude our work in Section V.

II. Related works

In Eschenauer-Gligor scheme[10], a large key pool of n keys is generated. Then, m keys are randomly selected from the n keys and aredistributed to each node. Therefore, any two nodes have one common key with a certain probability. For example, if n = 10000 and m = 83, the probability that two nodes have at least one common key is 50 %. Moreover, with an increase in the size of the key pool (n), the number of keys stored by each node (m) should be increased to maintain a certain connectivity. For example, if n = 100000 and the required connectivity is 50%(i.e., the probability that two nodes have at least one common key is 50 %), m must be greater than 260. This value is too large for resource-constrained sensor nodes. The Du et al. scheme proposed in [11] is one of the improvements of the Eschenauer-Gligor scheme. In this scheme, two nodes deployed to the same rectangle can share keys with a high probability because their subset key pools are the same. Two nodes deployed to neighboring rectangles share keys with a lower probability because their subset key pools have fewer common keys. If two nodes are deployed to non-neighboring rectangles, the probability of key sharing is zero. Therefore, the damage due to the compromise of one node is limited to neighboring rectangles, and hence, the network is resilient against node capture. This scheme assumes the group-based deployment model, and the deployment points should be horizontal grid points. For other deployment models, the mannersin which the target deployment area should be divided and the subset key pools should be generated are not clearly described and performing these tasks appears to be difficult.

Public-key cryptography is a possible solution for key establishment in wireless networks. Though recent work[7] demonstrates cases in which public-key cryptography can be implemented on some resource-constrained devices, it is not yet feasible for all multi-hop networks. In the absence of public-key protocols, key establishment must be performed using symmetric (shared) keys which are assigned to nodes prior to network deployment, a solution known as key pre-distribution. Another extreme solution is the assignment of a global key to every node in the network. However, if an adversary is able to obtain the global key, the security of the entire network is compromised. A promising approach to symmetric key assignment which attempts to balance the trade-offs between complexity, storage and security is the star key graph based[8] key assignment. Through star key assignment, the complexity of public key protocols, the storage overhead of pair-wise key protocols and the easy compromise of global key protocols can be mitigated. Our scheme shows that each of the ordinary sensor nodes needs to maintain only 3keys. Furthermore, most solutions did not address node re-keying or security at different levels of granularity. Our solution, on the other hand, assigns different level of security loads according to resource capability and is applicable to members that are affiliated subgroups of nodes.

Ⅲ. Group-based security scheme

In this section, we model the group-based security scheme. Prior to network deployment, initial secret keys are assigned which is termed as key pre-distribution. Then the sensor nodes are deployed into the area of interest and the secure group-based network formation is described. Post-deployment re-keying is presented at the end of this section.

1. Key Pre-distribution

In the offline key pre-distribution phase, we assign the group keys and individual keys to a group of nodes. For this, the key assignment is accomplished according to Fig. 1.

Each GD holds the group key K_G and all the individual keys of SNs, $K_{SN_1}, \cdots, K_{SN_Z}$ where Z is the number of ordinary sensor nodes in a particular group. Each SN holds group key K_G and its individual key K_{SN} shared with GD. There is also a shared key between BS and each SN and a sheared key between BS and each dominating node (not shown in fig. 1).

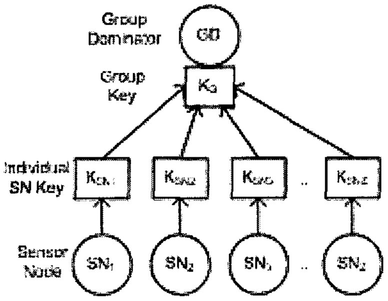


그림 1. 스타 키 그래프를 이용한 키 분배
Fig. 1. Key distribution using star key graph.

2. Network Model

We devise a 3-tier sensor network composing three types of nodes. The BS is considered as resourceful enough in terms of residual energy, computation power and speed, and communication. We assume that SN is simple, inexpensive and stringent in resources, while GD is rich in resources and more compromise-tolerant and having transmission range more than 2*R_{SN}, where R_{SN} is the transmission range of an ordinary SN. We also assume that one GD can communicate with its neighbor GD to forward aggregated messages towards the BS. The connectivity (and routing) from the sensor to the BS is dependent on the pre-distributed secret keys. We assume that all the SNs and GDs are static after they are deployed in the deployment field (e.g., disaster management, forest fire detection). The final locations of the nodes differ from each other after the deployment. However, we assume that the final locations of a GD and its children SNs follow the same probability distribution function. The detailed deployment model is described below.

The GDs and SNs that are to be deployed are divided into n groups {Gi | i =1,2,⋯,n} according to the group and sensor-GD pair-wise keys. A Single

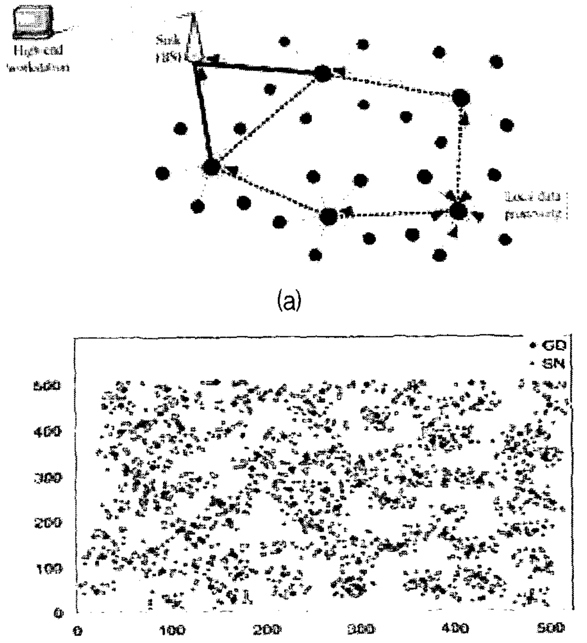
GD and Z sensor nodes form a group. We assume that the groups are evenly and independently deployed on the targeted field. The nodes in the same group Gi are deployed from the same place at the same time with the deployment index i. During the deployment, the resident point of any node in group Gifollows a probability distribution function f(x, y), which we call the deployment distribution of group Gi. The actual deployment distribution is affected by many factors. For simplicity, we model the deployment distribution as a Gaussian (Normal) distribution[9] since it is widely studied and proved to be useful in practice.

Let us assume that V_{BS}, V_{GD} and V_{SN} are the sets of BS, GD and SN respectively and $G(V,E)$ represents entire network in the graph model where, $V=\{V_{BS} \cup V_{GD} \cup V_{SN}\}$. The network backbone $G_B(V_B, E_B) \subseteq G(V,E)$ is formed by the GDs and base stations, provided that, all GDs present in the backbone have at least one path between each-other; i.e., each GD has a BS within itstransmission range or has another GD that can communicate with any of the BS, and, at least one path exists between the backbone and a BS. The SNs form GD rooted local groups (Fig. 2) by pair-wise and group keys. Hence the connectivity between a SN and its parent GD depends on two basic conditions:

i) $d(x,y) \leq R_{SN}$, where x is a SN, y is a GD node, $d(x,y)$ is the distance between two nodes x and y, and R_{SN} is the transmission range of SN, and,

ii) $Groupkey_{GD} = GroupKey_{SN}$.

Fig. 2 shows typical group-based deployment scenario according to our proposed model. In the figure, GD represents the local group dominator and SN represents the constrained sensor nodes. Ordinary nodes are connected locally to its GD and all the GDs are connected network-wide (i.e. backbone network). The backbone network formed by GDs is connected to the BS and thus, the whole network is connected.



(a)

(b)

그림 2. 그룹 형성 시나리오
(a) 기본적인 그룹기반 토폴로지
(b) 제안된 그룹 형성 모델을 사용한 토폴로지

Fig. 2. Deployment scenario. (a) Desired group-based topology. (b) Observed topology from proposed deployment model.

표 1. 그룹 기반 적용 모델의 연결성

Table 1. Connectivity of the group-based deployment model.

GD	SN	In Group	Out of Group	Out of Network	Connectivity (%)
200	3000	2382	189	429	85.70
300	3000	2371	197	432	85.60
300	4500	3571	286	643	85.70
300	6000	4719	421	860	85.60

Table 1 shows the observed connectivity of proposed group-based deployment model. We take different number of GDs and ordinary SNs with their group key and transmission range. More than 85%sensor nodes fall within the overall network in which they are connected by their GD or other GD (out of group)

3. Secure Network Formation

After the deployment, each SNi discovers its own GDj. For this purpose, SNi broadcasts an encrypted SN_JOIN_REQ (using individual key KSNi) message to all of the nodes within its transmission range. If the corresponding GDjis within its transmission range (i.e., one hop distance), it gets the message and decrypts it as all the individual keys of the sub-ordinate nodes are known to the GDj. Upon successful decryption of the message, the GD sends a JOIN_APPROVAL message to the SNi encrypting it with the group key (Shared among SNi in GDj). Thus the SNibecomes a dominated node of this corresponding GDj. If, for any SNi, the GDj assigned during pre-distribution of keys, is not within one hop distance; the SNineeds to inform the BS for resolving the issue. On discovering itself as out of its own GD, the SNi sends a GD_ERROR message encrypting it with its individual key. This message is simply forwarded by other sensors and GDs in the network to reach to the BS. For resolving the unexpected issue of this kind, two special cases are considered.

Case I The SN has no dominator as its one-hop neighbor. In such a case, after getting the GD_ERROR message from the SN, the BS issues a command COMM_GD to assign the role of a GD to this SN. For sending the command, the BS uses the individual key of the SN. This newly formed GD does not have any other dominated SN; however, employing this method keeps the isolated node connected with the rest of the network.

Case II The SN does not have its own GD within its one-hop neighborhood but another GD is available in the vicinity. Failing to find out its own GD, SN sends the encrypted GD_ERROR message to the BS. Now, as the GD of another group is present within its one hop distance, it gets the encrypted GD_ERROR message (only detects the type of message and just notes this incident), informs this message encrypted with its group key to the BS. The BS checks the message and issues a command COMM_AGD to that neighbor GD to be its adopter and also sends the individual key for this SN. The GD in turn uses this key to send its group key, K_G, to the SN to welcome it in its own group. Thus, all the groups can form the overall network backbone where the GDs of the logical groups are the dominating nodes and all other nodes in the network are dominated.

4. Local Data Processing and Forwarding

Once the network is logically structured as a group-based distributed network, the sensory data can be transmitted securely to the BS. If there are Z number of SNs in a group, for fidelity and correctness of data, the GD waits for the same sensing event from at least q (q ≤˜Z) number of the SNs, where q is the threshold value set for a particular group. We consider any one group with ordinary SNs and its corresponding GD. Once an event occurs, q out of Z (0 ≤˜q ≤˜Z) ordinary sensors (ID1, ID2, . . ., IDq) within the sensing area detect the event and send information to the GD. The message aggregation is accomplished in the following manner:

$$SN_i \rightarrow GD_j : ID_i | E(M_i | MAC(M_i, K_{(SN_i, GD_j)}), K_{(SN_i, GD_j)}))$$

where, ith SN belongs to jth GD, K(SNi, GDj) is the shared key between SN and corresponding GD, E(.) is the encryption, and | denotes bitwise XOR operation, and MAC is the message authentication code. Upon receiving the message sensed by SNi, dominator GDjverifies every single MAC and generates an aggregated report (and discards the false packet if any).

All the SNs in a particular group j also creates a MAC using the shared key between SN and BS and this MAC is only to be verified by the BS but to be relayed by its GD. The message format is: $SN_i \rightarrow GD_j : ID_i | MAC(K_{(SNi, B)})$, where, K(SNi, B) is the shared key between a SN and a BS. Now, GD collects all the MACs from ordinary sensor nodes and sends q MACs, q IDs, IDGDj, and MGDj to the BS directly or via its neighboring GD (multi-hop path through consecutive GDs towards the BS) as follows.

$$GD_j \rightarrow Sink : ID_{GDj}, E(K_{(GDj, B)}, ID_{GDj} | M_{GDj} | ID_1 | \\ MAC_{(SN1, B)} | \cdots ID_q | MAC_{(SNq, B)})$$

The q MACs and an aggregated report MGDj are sent securely to the BS. Upon receiving the aggregation report, the BS first decrypts the message using the corresponding key $K_{(GDj,B)}$, then it checks whether the report carries at least q distinct MACs from ordinary sensors and whether the carried MACs are the same as the MACs it computes via its locally stored keys. If no less than q MACs is correct, the event is accepted to be legitimate; otherwise it is discarded.

5. Post-deployment Re-keying

When any new node is deployed, it sends the JOIN_REQ_NEW message using its own individual key and, if authorized by the access list of GD, it joins the group. Otherwise, GD forwards this to BS. BS informs GD about the individual key of that SN. If authenticated by BS, GD generates a new group key and encrypts the new group key with the newly added node's individual key and sends it to the SN. For example, let's say, SN4 in Fig.3wants to join the existing group in the figure shown above. GD changes the group key KG to a new key KGnew, and encrypts it with the old group key and sends $GD_j \rightarrow allSN_i : E_{K_G}(K_{Gnew})$ to all sensors.

And GD encrypts new group key with the joining SN's individual key and sends $GD \rightarrow SN_4$: $E_{K_{SN4}}(K_{Gnew})$. Similarly, when any SN wants to leave the group, it just sends a leave message, $SN_4 \rightarrow GD : E_{K_{SN4}}(leave)$. Upon receiving the leave message, GD deletes the leaving SN4 and updates the KG to a new KGnew, encrypted with remaining SN's individual key and unicasts the message $GD \rightarrow SN_{i-1} : E_{K_{SNi-1}}(K_{Gnew})$. In this way, the key management for a new node join/leave can be handled.

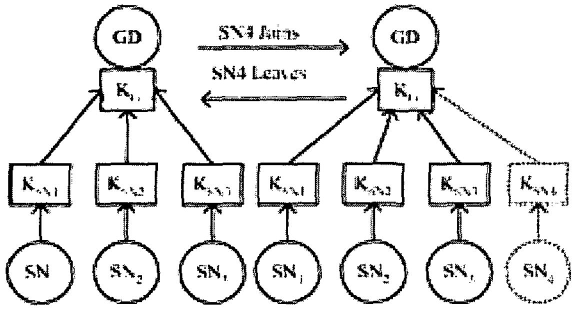


그림 3. 로컬 그룹에서 노드 가입과 탈퇴를 위한 키 관리 메커니즘

Fig. 3. Re-keying mechanism in a local group (node join/leave)

Ⅳ. Security analysis

We contemplate on analyzing the threat posed by compromising the ordinary SNs and GDs. An adversary may jeopardize the group-based network in the following ways: First, an adversary can simply deploy some malicious ordinary SN into a group. A malicious sensor without having the secret key may try to produce a false sensing result with an identity of a legitimate sensor. Since, a malicious SN does not have the capability of producing a valid MAC for the false sensing result, the GD will identify it. Second, an adversary can copy some ordinary SNs from some group and deploy them into another group. As each GD knows the set ohiaf ordinary SNs within its own group, a GD is able to identify an illegitimate ID of ordinary SN. Nevertheless, an ordinary compromised SN can not fool the GD of another group without knowing the valid key. Similarly, a compromised GD from one group does not fool the ordinary SNs of another group without knowing the valid keys. Third, given any group having a GD and Z ordinary SNs, an adversary may launch attack in three ways: (a) compromise some SNs only, (b) compromise the GD only, and (c) compromise the GD and some SNs concurrently. We term this security threat as intra-group node capture. And fourth, an adversary may launch attack in a distributed manner: (a) randomly compromise ordinary SNs throughout the entire network and/or (b) intelligently compromise few GDs where maximum number of ordinary SNs has already been captured. We term this security threat as network-wide node capture. In the rest of this section, we analyze intra-group and network-wide node capture attacks.

1. Intra-group Node capture

a. Ordinary sensors nodes are captured

A compromised ordinary sensor in a particular group may produce an invalid MAC by providing wrong guarantee for an aggregated report. The group-based scheme is robust against this kind of attack as long as no more than qsensors within a local group are compromised. Since we devise our scheme where each aggregated report carries q number of MACs from ordinary sensors.

b. Only the group dominator is captured

When a GD is captured, it may fabricate a report. But to do that, at least qMACs need to be forged. The probability that at least q out of Z MACs is correct is given by $p_{GD} = \sum_{j=q}^{Z}\binom{Z}{q}p^{q}(1-p)^{Z-q}$, where, p = $1/2^{L}$ and L is the MAC size in bits. It can be seen that this probability p_{GD} is negligible for 4-byte CBC MAC[14]; moreover, only one group out of the entire network is in fact affected while other groups are not.

c. Group dominator and sensor nodes are captured

We consider the situation where an adversary has compromised a GD and some number x (0 ≤ x ≤ q) ordinary sensor nodes concurrently. To inject a false report, a GD needs at least q valid MACs. Since a GD has to forge (q − x) more MACs, the probability that (q − x) out of (Z −x) is valid, is given by

$$p_{GD}^{x} = \sum_{j=q-x}^{Z-x}\binom{Z-x}{j}p^{j}(1-p)^{Z-x-j}$$

Again, this probability is almost negligible[14]. If an individual key is compromised, the attacker at best could send false report to the GD but when any message from the GD comes encrypted with the group key, it cannot decrypt it.

2. Network-wide Node Capture

We analyze the robustness of our scheme when an adversary has randomly compromised Q (0 ≤ Q ≤ N) ordinary SNs and j (0 ≤ j ≤ Y) GDs from the entire network. Let p (j, q) be the probability that jth GD (i.e., jth group) having q (0 ≤ q ≤ Z) SNs compromised, we get

$$p(j,q) = \frac{\binom{Z}{q}\binom{N-Z}{Q-q}}{\binom{N}{Q}}$$

We define gj ,q as:

$$g_{j,q} = \begin{cases} 1, \text{if ordinary senor nodes are captured in } j^{th} \text{ group} \\ 0, otherwise \end{cases}$$

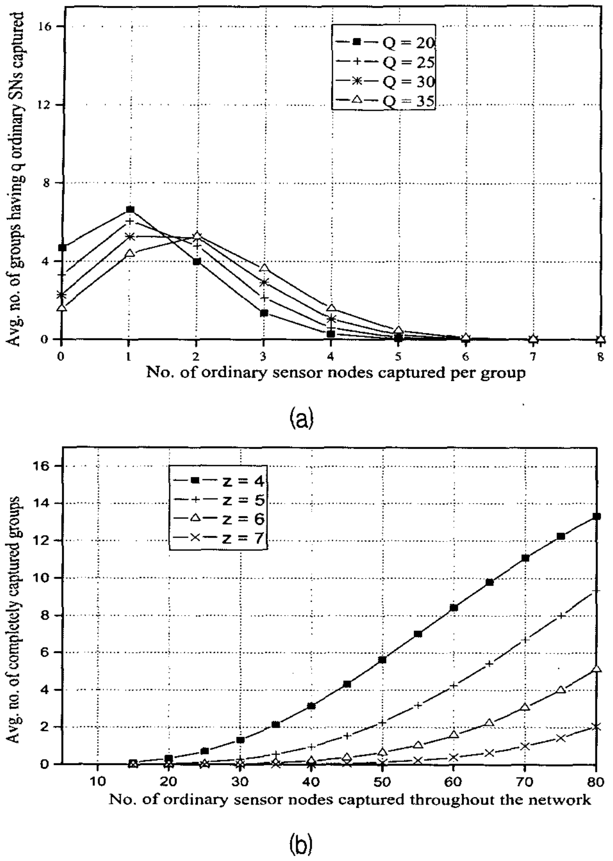
And let Gq denote the number of groups having q ordinary SNs captured from the entire network, we get $G_q = \sum_{j=1}^{Y} g_{j,q}$ and, the expected number of groups having q ordinary SNs captured can be calculated by the following equation:

$$E\left[\sum_{j=1}^{Y} g_{j,q}\right] = \sum_{j=1}^{Y} E[g_{j,q}] = Y.E[g_{j,q}]$$
$$= Y.p(j,q) = Y.\frac{\binom{Z}{q}\binom{N-Z}{Q-q}}{\binom{N}{Q}}$$

Next, we assume that an adversary has captured some groups having the z (z ≥ q) SNs compromised and we call this situation as a complete group capture. Let X be the number of completely captured groups from the entire network. We can compute E[X] by the following equation:

$$E[X] = \sum_{q=z}^{Z} G_q = \sum_{q=z}^{Z} Y\frac{\binom{Z}{q}\binom{N-Z}{Q-q}}{\binom{N}{Q}}$$

For demonstration purpose, we take a simple example where total number of SNs is N=170, with Z=10 SNs in each group (i.e., Y=17 groups). Fig.4a shows the expected number of compromised groups against the entire network's compromised ordinary SNs. When 20 SNs are captured, 5 groups having 0



(a)

(b)

그림 4. 정량적 분석: 노드 캡처 공격에 대한 네트워크 보안 강도(N=170, Y=17, Z=10)

Fig. 4. Quantitative analysis: network-wide robustness against node capture attacks (N = 170, Y = 17, Z = 10).

SNs compromised and only 1 group having 3 SNs compromised. Fig.4b demonstrates the number of fully compromised groups that depends on the value z. Four cases are shown when z is 4, 5, 6 and 7. When z is 4, 3 (16.66%of entire network) groups are fully compromised against 40 (23.5%) ordinary compromised SNs. But, as the value of z increases (e.g., 6 or 7), number of fully compromised groups are much smaller. We observe that robustness can be improved significantly by increasing the value of z.

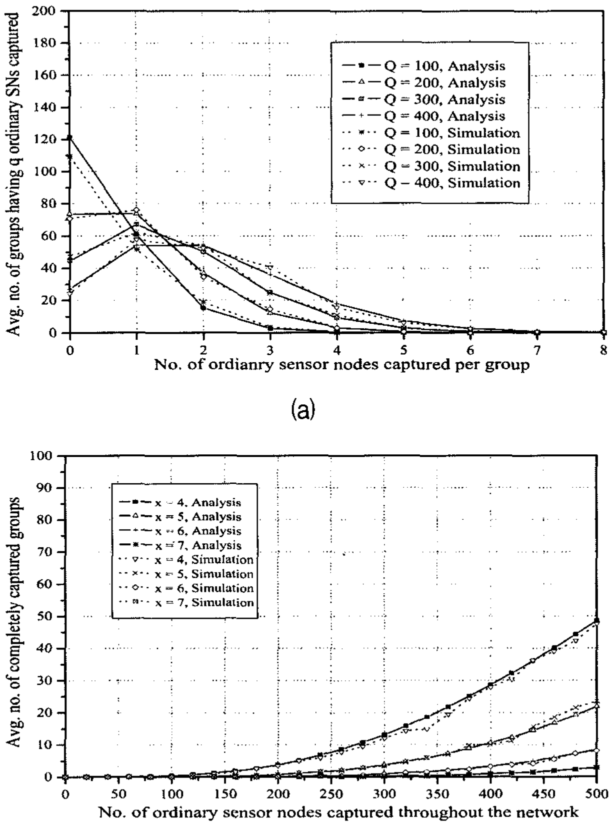
Next, we use the properties of Poisson Process to analyze the robustness of our scheme. We consider the case where the number of compromised SNs Qis much less than the total number of SNs N (i. e. Q « N). We denote the status of any sensor in a particular group as Ci, for i = 1, 2, . . . , Z and consider it as Bernoulli random variable. Let Ci = 1, if the ith sensor is captured and Ci = 0, if not captured. Considering the Qcaptured SNs are uniformly distributed across the network, probability of any SN captured by an adversary can be given by $p[C_i = 1] = Q/N, i = 1,2,\cdots,Z$. If the condition Q « N holds, then, C1, C2, . . . , CZ are said to be independent according to the properties of Poisson Process[13] and the number of captured sensors in a particular group follows the Poisson distribution with approximated mean value Q/Y. So, if q sensors are captured in a group, we get the probability as $p[q] \approx e^{-Q/Y}\frac{(Q/Y)^q}{q!}$. Now, if the total number of groups is Y, we calculate the expected value of the number of groups Y having q sensors captured as:

$$E[Y_q] \approx Y.e^{-Q/Y}\frac{(Q/Y)^q}{q!}$$

Next, considering the case where an adversary has captured some groups having the x (x ≥ q) SNs captured and we call this situation as complete group capture. Let Xbe the number of completely captured groups from the entire network. We can compute the expected value E[X] by the following equation:

$$E[X] \approx \sum_{q=x}^{Z} Y_q \approx \sum_{q=x}^{Z} Y.e^{-Q/Y}\frac{(Q/Y)^q}{q!}$$

Robustness against node compromise has been plotted in Fig. 5 using the analytical result calculated from Poisson Process as well as the results obtained by simulation. The results are almost similar as can seen in Fig. 5. Fig. 5a shows the average number of groups where q (0 ≤ˇq ≤ˇZ) ordinary SNs are compromised by the attacker in each individual group. 37 groups having 0 and 18 groups having 2 SNs compromised when Q = 100SNs are captured from the entire network. Worst case scenario in our approach, when 400 SNs are capture network-wide, only 18 groups out of 100 having 4 SNs captured. Fig. 5b shows the average number of groups that are fully captured when more than q (q ≤ˇx ≤ˇZ) sensor nodes are captured.. For the values x equals 4, 5, 6 and 7, we realize that for x = 4, 73% groups are fully captured when 25% SNs are captured



(a)

(b)

그림 5. 포이송 분석과 시뮬레이션: 네트워크의 보안 강도 (N = 3000, Y = 200, Z = 15)

Fig. 5. Poisson analysis and simulation: network-wide robustness.(N = 3000, Y = 200, Z = 15)

throughout the network. But, as the value of x increases, its robustness gets stronger. For example, x = 7, 23% (23 out of 100) groups are captured for 25% (500 out of 2000) network-wide captured SNs. So, significant improvement in network robustness can be achieved by increasing the value of x.

Fig. 6 plots our analysis when the deployment density is increased in terms of ordinary SNs and GDs. Poisson analysis reveals the fact that the expected number of groups having q ordinary SNs captured in each group is independent on the low and high deployment density. However, the effect on the complete group compromise is significant. It can be seen from Fig. 6 that when x = 10, and Q = 1000 (i.e. 16.66%) ordinary captured nodes leads to only 0.70 (i.e. 0.23%of entire groups) groups to be completely captured. Hence, robustness may significantly be enhanced by increasing the number of SNs as well. Interested readers may verify that network robustness can also be improved by increasing the number of group dominators (i.e. dividing deployment area into more groups).

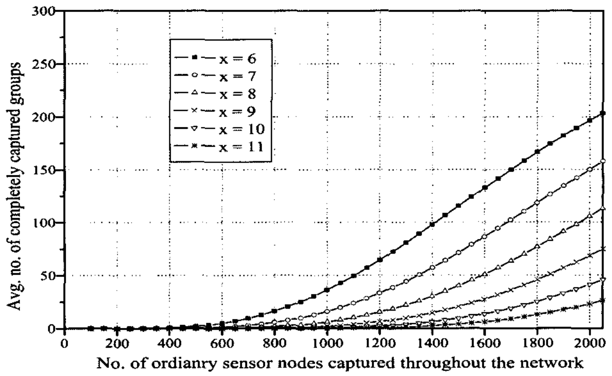


그림 6. 배치 밀도에 따른 영향 (N = 6000, Y = 300, Z = 20).

Fig. 6. Impact of deployment density. (N = 6000, Y = 300, Z = 20)

V. Conclusion

We develop a hierarchical group-based secure network in which sensed information is processed locally by the dominating node that prepares an authenticated report for the destination. We have shown that star based key pre-assignment has significantly less storage overhead for the individual constrained sensor node. We evaluate our scheme through analysis and simulation to show that group-based architecture is strongly resilient to node capture attacks. It is shown that the robustness capability of the group-based network manifests itself not only in the number of sensor nodes, but also in the number of superior group dominating nodes. Some implications may be worth considering by the implementers: the proposed model suggests that nodes can be grouped into small clusters or cells where in each cell one can designate a specific node (group dominator in this case) to carry all the burden of relaying multi-hop packets. Thus a division of labor is possible to make the overall scheme to be profitable. Nevertheless, it would further reduce the transmission power consumed by the vast majority of other ordinary nodes.

References

[1] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next century challenges: Scalable coordination in sensor networks," in Proc. of ACM Mobicom, Seattle, Washington, USA, August 1999, pp. 263 - 270, ACM.

[2] C. Intanagonwiwat, D. Estrin, R. Govindan, and J. Heidemann, "Impact of network density on data aggregation in wireless sensor networks," in ICDCS, 2002, pp. 457 - 458.

[3] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks,"in MOBICOM, 2000, pp. 56 - 67.

[4] B. Krishnamachari, D. Estrin, and S. Wicker, "The impact of data aggregation in wireless sensor networks," inInternational Workshop on Distributed Event-Based Systems, (DEBS '02), Vienna, Austria, July 2002.

[5] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A Survey on sensor networks," IEEE Communications Magn, vol. 40, no. 8, 2002.

[6] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," Computer Networks, vol. 38, no. 4, March 2002.

[7] N. Gura, A. Patel, A. Wander, H. Eberle, S. C. Shantz, "Comparing elliptic curve cryptography and RSA on 8-bit CPUs," in Proc. of the Sixth Workshop on Crypto- graphic Hardware and Embedded Systems (CHES'04), Cambridge, MA, USA, 2004, pp. 119 - 132.

[8] C. K. Wong, M. Gouda and S. S. Lam, "Secure Group Communications Using Key Graphs", IEEE/ACM Trans. on Networking, Vol. 8, No. 1. February 2000.

[9] Donggang Liu, Peng Ning, and Wenliang Du., "Group-Based Key Pre-Distribution in Wireless Sensor Networks," inProc. ACM WiSE'05, September 2, 2005.

[10] L. Eschenauer and V. D. Gligor, "A key-management scheme for distributed sensor networks," in Proc. of the 9th ACM Conference on Computer and Communications Security, pp. 41 - 47, November 2002.

[11] W. Du, J. Deng, Y. S. Han, S. Chen, and P. K. Varshney, "A key management scheme for wireless sensor networks using deployment knowledge," in Proc. of the IEEE INFOCOM, pages 586 - 597, March 2004.

[12] G.J. Pottie, and W.J. Kaiser, "Wireless integrated network sensors," Communications of the ACM 43 (5) (2000), pp. 551 - 558.

[13] S. M. Ross, Introduction to Probability Models, Academic Press, 2003, 8th Edition.

[14] Y. W. Law, J. Doumen, and P. Hartel, "Survey and benchmark of block ciphers for wireless sensor networks," ACM Trans.on Sensor Networks, vol. 2, No. 1, pp. 65 - 93, February 2006.

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