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Group Key Distribution via Local Collaboration in Wireless Sensor Networks

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Abstract— **In this paper we propose a group key management scheme for sensor networks that targets at fast response to changes in security conditions. Motivated by the fact that a compromised sensor is most likely to be first detected by its fellow neighboring nodes, we introduce the concept of local collaboration during the process of group key distribution. In the proposed scheme, a sensor node is not able to obtain the secret key solely based on the broadcast message and its pre-deployed secret share. Rather, it has to seek for collaboration from its fellow sensor nodes. Only by jointly exploiting the secret shares disclosed by the broadcast message, its own pre-distributed secret, as well as secrets revealed by other nodes, can a node reconstruct the group key. By empowering the sensor nodes themselves to be able to exclude a compromised node, the scheme promises fast reaction to the ever changing network condition. Furthermore, we provide a set of enhancements to the basic scheme including self-evolving design for significant reduction in communication and memory overhead.**

***Index Terms*: key management, sensor networks, broadcast, local collaboration**

I. Introduction

As wireless sensor networks are sprinting toward wide deployment in a plethora of application environments [1, 2], security remains one of the most critical challenges yet to be fully addressed. While tremendous efforts have been devoted to providing security mechanisms in conventional wireline and wireless networks, direct importing most of the existing results unfortunately has been nullified by the unique characteristics of wireless sensor networks. The reasons are three-fold. First, sensor nodes are constrained by *scarce resources* in terms of both computing and energy. This implies that computational hungry and/or communication hungry methods are inherently infeasible. Secondly, sensor nodes can be easily compromised in an unattended or hostile environment and thus conduce to an *untrustworthy network*. Finally, the presence of a vast number of nodes has dictated that the security scheme must be *scalable* while being obliged to work without centralized controllers.

In the heart of any security schemes is the key management mechanism responsible for distributing secret keys. Recently, an extensive set of papers have studied both pairwise key management schemes [3–7] and group key management schemes [8] for secure communication in wireless sensor networks. Notably several key distribution schemes have been proposed that are capable of delivering personal and group keys with self-healing and revocation capability [9, 10]. The key idea is to broadcast information that is useful only for trusted nodes. Combined with its pre-distributed secrets, this broadcast information enables a trusted sensor node to reconstruct a shared key. On the contrary, a revoked node is unable to infer useful information from the broadcast and hence is denied of access. *Unfortunately, these schemes demand that compromised identities are fully recognized at the basestation. Gathering of such information incurs long delay and hence inevitably introduces security holes owing to information inconsistence.*

In this paper, we develop an efficient key management scheme for secure broadcast in resource limited sensor networks. *Our objective is to simultaneously attain efficiency, revocability of compromised nodes, and fast reaction and adaptation to time-evolving security situations.* Towards this end, we propose an innovative group key distribution scheme that is not only based on pre-distributed personal secrets and broadcast information, but also require local collaboration among sensor nodes themselves. To be more specific, a sensor node is not able to obtain the secret key solely based on the broadcast message and its pre-deployed secret share. Rather, it has to seek for collaboration from its fellow sensor nodes. Only by jointly exploiting the secret shares disclosed by the broadcast message, its own pre-distributed secret, as well as secrets revealed by other nodes, can a node reconstruct the key.

This approach promises timely response in parallel with confidentiality to dynamic network situations. Compromised nodes are likely to be first identified by neighboring nodes, for example, by observing abnormal routing or transmission behaviors. Indeed, detailed methods for detecting compromised nodes via such an approach have been proposed [11–13]. By allowing sensor nodes to make local decisions on whether to collaborate with a fellow node based on its own judgement, the scheme provides the promptest reaction possible to the ongoing changing security circumstance. At the same time, dependent on its evaluation of current network security, the base station can vary the amount of secret that it shall disclose in the broadcast message and consequently dictate the number of nodes must be involved in order to collaboratively decrypt the broadcast key. As time evolves, more and more nodes will be compromised in a neighborhood and hence our approach will request a node to be trusted by more neighbors in order

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to obtain the secret which in turn will provide dynamic adjustments to the network condition not achieved by previous schemes.

In addition, we propose a set of enhancements to the above scheme, including self-healing capability to accommodate the lossy nature of the wireless medium. In particular, we develop a self-evolving scheme that allows sensor nodes to advance their personal secrets from session to session and hence reduce significantly the requirement on memory for storing pre-deployed secrets.

The reminder of this paper is organized as follows. In section II, we define the system model and present some preliminaries. The baseline scheme for the proposed key management mechanism is described in Section III together with enhancements for multiple session support and self-healing. Section IV discusses the self evolving scheme for memory reduction followed by detailed discussion on related work in Section V. Finally, we conclude in Section VI.

II. System Model and Preliminary

We consider a large wireless sensor network deployed in a hostile environment such as a battlefield [14, 15]. The network lifetime is divided into time intervals known as *sessions*. The length of each session may or may not be equal depending upon the network conditions [10]. Sensor nodes deployed in the network are resource constraint in terms of processor speed, memory storage and power supply [16]. Sensors within the network can either be of low mobility or fixed as our schemes are not location dependent. However, mobility will affect the performance of the system in terms of timely detecting compromised neighbors or establishing collaboration.

Key deployment and maintenance is managed by a central controller (broadcast station or central server) which is the *sink* for the entire network. The sink is responsible for picking group keys, preloading nodes with secret information and distributing secret shares from session to session. Sensor nodes in the network are uniquely identified by an ID number i, where $i \epsilon \{1, \cdots, n\}$ and n is the largest ID number. We assume a lossy channel and hence do not assume reliable communication in our system. A message sent out may or may not reach all the nodes in the network. Our focus for this paper is to enable the secure distribution of a *network wise session key* solely by broadcast from the sink and pre-deployed information on the sensors. In the remainder of this paper, we will term this key interchangeably as either a *session key* or *group key*.

We assume that attacks on the nodes in the network by the adversary can be passive or active attacks. Compromised nodes in the network arising due to adversarial attacks shall be revoked by the sink. By revocation, we mean that nodes shall be incapable of deriving the session keys once they are identified as compromised. We assume that compromised nodes can be detected by its neighbors using the watchdog mechanisms and/or some collaborative intrusion detection and identification schemes [12, 17]. Our motivation is that the sensor nodes shall be able to identify a compromised node faster than the sink itself due to the proximity and close interaction among neighbors.

Sensor nodes in the network establish pairwise keys for confidential peer to peer communications. An example scheme for establishing pairwise keys among sensor nodes is given in [3] where multiple bivariate polynomials are deployed on each sensor. This scheme is proved to be unconditionally secure and provides t-collusion resistance. In this work, we assume that broadcast messages sent from the sink can be authenticated by each sensor nodes and limit our scope of discussion only to confidentiality on distributing session keys.

A. Preliminary

The work in this paper employs existing schemes including threshold cryptography [18, 19] and self-healing key distribution mechanism [9, 10]. Generally speaking, threshold cryptography [18] is used for distribution of trust in key management and an (n, k) threshold scheme allows n parties to perform cryptographic operations, so that any k parties can jointly perform key discovery whereas $(k - 1)$ parties cannot derive any information even after collusion. A sample threshold cryptography scheme proposed by Shamir can be explained as follows. Consider a number D chosen as the secret, we can store the secret about D into n pieces via a randomly chosen k degree polynomial $f(x) = a_0 + a_1 x + \cdots + a_{k-1} x$ where $a_0 = D$. The n pieces of secrets are simply $\{f(1), f(2), \cdots, f(n)\}$. Given k points from the above n pieces, we can derive the coefficients of $f(x)$ by interpolation and hence calculate the secret $D = a_0$. On the contrary, coalition of $k - 1$ points reveals no information about D. Therefore, the above scheme is a (n, k) threshold cryptography scheme.

Key distribution schemes for sensor networks with self-healing capability was first proposed in [9] and later on improved in [10]. While we are going to employ the latter scheme in our design, the former one will serve well the same purpose. The scheme is capable of distributing both personal keys and group keys in a particular session based purely on broadcast. This is achieved by the construction of a polynomial broadcasted from the sink which can be written as $w(x) = f(x).g(x) + h(x)$. Here, $h(x)$ is the masking polynomial whose value on point i is pre-deployed to node i; $g(x)$ is the revocation polynomial constructed as $(x - r_1)(x - r_2) \cdots (x - r_w)$ where $\{r_1, \cdots, r_w\}$ is the set of compromised nodes; and $f(x)$ is the secret polynomial which would provide the personal secret to each node. Node i can evaluate the polynomial $w(x)$ at point i and derive its personal key as $f(i) = \frac{w(i)-h(i)}{g(i)}$. On the contrary, a revoked node j will not be able to derive its personal key as $g(j) = 0$. Since the value of $h(i)$ is securely pre-deployed and $f(x)$ is randomly chosen, the scheme can be proved to be unconditionally secure.

A group key distribution scheme is also proposed in the paper by utilizing a similar approach where threshold cryptography is utilized and enhancement for self-healing is also discussed. For this purpose, the group manager splits the group key K_j for session j into two polynomials, such that

$K_j = p_j(x) + q_j(x)$. $p_j(x)$ and $q_j(x)$ are then distributed to select group members via broadcast. Similar to personal key distribution, any non-revoked node i is able to evaluate the broadcast message and obtain $p_j(i)$ and $q_j(i)$. The group key can then be calculated by adding up the two session shares.

In the next section, we will introduce the concept of local collaboration into the scheme of key distribution. While the approach is similar in that we also rely on broadcast from the sink and pre-deployed knowledge for personal key construction, local collaboration renders various advantages including fast response to newly compromised nodes and adaptive adjustment of broadcast content for time evolving network conditions.

III. Group Key Distribution via Local Collaboration

In this section we develop a group key distribution scheme that is not only based on pre-distributed personal secrets and broadcast information, but also requires local collaboration among sensor nodes themselves. Only by jointly exploiting the secret shares disclosed by the broadcast message, its own pre-distributed secret, as well as secrets revealed by other nodes, can a node reconstruct the key. The key challenge then is the process of local collaboration itself. If during the process, personal secret is disclosed, it is equivalent that the sensor is compromised by its fellow node. However, at the same, to derive the network wise group key, which is actually hidden in the broadcast message, a node has to seek trust and exchange secrets with others. Our solution to this is to employ a *concealing secret* to mask true personal key before sharing it with other trusted nodes. Enough concealed secrets will indeed enable sensors to derive the group key while preventing the revealment of any personal secret among them.

Below, we first present the baseline, one-time scheme for distributing group keys through both broadcast and local collaboration and next extend it to be capable of handling multiple sessions. Various enhancements will then be discussed and security and complexity of the scheme will be analyzed.

A. Baseline Scheme for One-time Key Distribution

Initially, all sensor nodes are pre-deployed with their respective personal secrets which are points on a polynomial randomly chosen by the sink. Let $h(x)$ be the chosen polynomial in F_q, the *personal secret* of node i is then computed as $h(i)$. Alongside, a *concealing secret* $l(i)$ based on a randomly chosen polynomial $l(x)$ is also deployed at node i. After the initialization, the group key is distributed via broadcast from the sink. Based on the broadcast message in conjunction with the pre-deployed personal key $h(i)$, node i is able to recover its personal key $f(i)$, the evaluation of a secret polynomial $f(x)$ at point i. At the same time, a revocation polynomial $g(x)$ within the broadcast message is capable of revoking nodes which are deemed to have been compromised. Owning the personal key, however, does not empower a node to be able to decrypt any broadcast message from the sink encrypted using the *session key*. Instead, it has to collaborate with a threshold number of other nodes in order to obtain the session key. This is done by obtaining other nodes' trust and hence their concealed secrets. The challenge is that nodes shall not directly exchange their personal secrets ($h(\cdot)$ or $f(\cdot)$). Our approach is to use the concealing secrets pre-deployed to mask these secrets before disclosing them. A node gaining enough concealed shares is capable of interpolating the values and deriving the current group key.

The details of the baseline scheme is described below and illustrated in Fig. 1.

<u>*Baseline Scheme:*</u>

Setup:

The sink randomly selects a $2t$ degree masking polynomials $h(x) \in F_q(x)$ where $h(x) = a_0 + a_1 x + \cdots + a_{2t}x^{2t}$. Correspondingly, sensor node i obtains personal secret $h(i)$. At the same time, a concealing polynomial $l(x)$ of degree t is also selected by the sink and node i is assigned concealing secret $l(i)$. Observe that $h(i)$ and $l(i)$ shall be pre-deployed or distributed via secure channels between the sink and each node.

Broadcast:

Given a set $R = \{r_i\}$, $|R| = w \leq t$, of the identities of compromised nodes known to the sink, the broadcast message B to distribute personal keys via t degree polynomial $f(x)$ to non-revoked nodes is constructed as $B = \{R\} \cup \{w(x) = g(x)f(x) + h(x)\}$, where the revocation polynomial $g(x)$ is constructed as $g(x) = (x - r_1)(x - r_2)\cdots(x - r_w)$.

Personal Key Recovery:

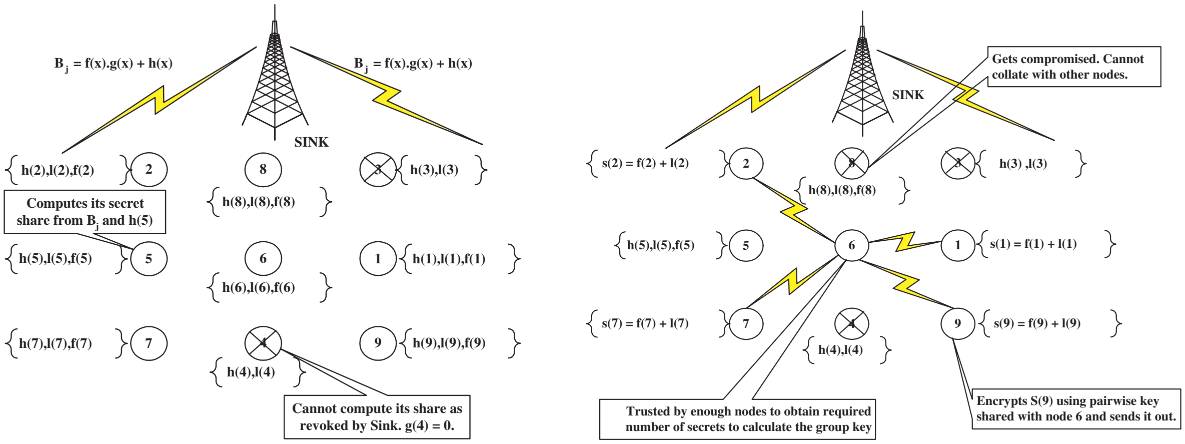
Upon receiving the broadcast message, any non-revoked node i can evaluate $w(x)$ at point i and derive its personal key as $f(i) = \frac{w(i)-h(i)}{g(i)}$. On the contrary, any revoked node j will be incapable of obtaining a new personal secret as $g(j) = 0$ and $h(i)$ is the personal secret only known to node i.

Local Collaboration:

To derive the group key, node u shall seek assistance from t fellow nodes. Towards this end, it shall broadcast this request to its neighbors. Upon the reception of this request, node i, willing to trust u, shall send a *concealed personal key* $s(i)$ to node u. Here, $s(i)$ is constructed as the summation of node i's personal key and its concealing secret, i.e., $s(i) = f(i) + l(i)$. Note that the communication from i to u for conveying this concealed secret shall be confidential, which can be achieved by employing the aforementioned pairwise key scheme in the network.

Group Key Recovery:

If node u is successful in obtaining t nodes' trusts and hence their concealed secrets, it can derive the current group key by following the threshold secret sharing scheme proposed by Shamir [18]. Specifically, notice that the concealed secret $s(i)$ is a point on the polynomial $s(x) = f(x) + l(x)$. By



(a) Broadcast message from the sink distributes personal keys to non-revoked nodes only

(b) Local collaboration enables a node trusted by enough number of nodes to derive the group key

Fig. 1. Illustration of the baseline scheme

interpolating $(t+1)$ points on the same polynomial, node u can evaluate $s(0) = f(0) + l(0)$ and hence derive the group key as $K = s(0)$.

We observe that other methods can be used to exchange the secrets among nodes as well. For example, nodes can directly share their $f(\cdot)$ with other nodes and the group key can then be derived as $K = f(0)$. However, this way, $f(\cdot)$ shall not be used for any other security purposes. By concealing $f(\cdot)$ using secret $l(\cdot)$, we have an efficient method of enabling the collaboration while preserving the security function of $f(\cdot)$ and $l(\cdot)$ simultaneously.

Analysis of the baseline scheme

Theorem 1: Given that the local exchange of the concealed secrets is secure, the baseline scheme for group key distribution is unconditionally secure with t-revocation capability.

Proof: Based on the facts that $f(x)$, $h(x)$, and $l(x)$ are randomly chosen, the claim on unconditional secure can be easily obtained. Based on the fact that $h(x)$ is $2t$ degree and $l(x)$ and $f(x)$ are t degree, the t-revocation capability can be obtained based on Shamir's result [18]. ■

The above proof assumes that the local exchange of the concealed secrets is secure. However, in real deployments, the pairwise key scheme supporting this secure peer to peer communication may be compromised as well. The relationship between our group key management and the pairwise key management scheme shall be carefully addressed. Although this shall be scheme-specific, we remark that the threshold for pairwise scheme shall not be lower than the group key management scheme in the case that the security of the pairwise key scheme is also ensured to a certain threshold. Using a few example pairwise key schemes, we illustrate below how the two shall be integrate together.

Relationship with the pairwise key scheme

As the local collaboration utilizes the established pairwise key scheme for confidential exchanged about concealed secrets, the security and overhead of the pairwise key scheme employed will significantly affect that of the proposed group key management scheme as well.

To establish pairwise keys among sensors, a scheme based on multi-bivariate polynomials of a certain degree is proposed in [3]. Consider the special case that in this scheme a single polynomial (of degree t) is adopted to establish pairwise keys. In such a case, the adversary only needs to compromise $(t+1)$ nodes to be capable of obtaining all the pairwise keys in the system. Here, group key threshold (say $t^{'}$) has to be kept equal to or smaller than t (pairwise threshold) as once the pairwise scheme is broken, the attacker can eardrop any local collaboration and break the group key scheme as well.

Using multiple polynomials instead of a single polynomial to establish pairwise keys among nodes provides more resilience to adversarial attacks [3]. In this case, each polynomial of degree t has to be compromised by the adversary to break the entire system. Moreover, another enhanced property of multi-bivariate polynomials scheme is path key establishment between peers which provides more avenues to establish the key for a pair of nodes. Due to the grid based pre-distribution of polynomial shares, nodes which are not compromised can establish pairwise keys with high probability even if a few keys have been compromised between them. Under this scenario, there is no single threshold value in the pairwise key scheme to determine that network wise, the system is broken. Therefore, determining the threshold of the group key scheme shall be based on the specific application requirements.

Another example for pairwise key management is the random key pre-distribution mechanism described in [5, 20]. In this scheme, from the whole key space, a pool of keys is randomly chosen from which a subset of keys are deployed in each node. Two nodes having a common key can use it as their pairwise key. This scheme provides less security in the sense that compromising a single node reveals many keys (possibly used by others as well) to the adversary. Using this scheme along with group key requires that the threshold for group key be set according to the application requirement, as there is again no a single threshold number for the pairwise scheme dictating that the network is broken.

Moreover, it is desirable that local collaboration occurs in neighborhoods if possible so that the communication cost is reduced. Through different pairwise key schemes, it is generally possible for a particular node to negotiate a shared private key with its neighbors (one hop or multiple-hop) based on the pre-deployed knowledge. Although then the one time key establishment cost may have to be paid, during the normal operation of the sessions, communication cost can be saved. Obviously, if a node deems its fellow neighbors not trustable as time evolves, it may have to seek the help from nodes farther away.

In view of the fact that, different pairwise schemes provide different levels of resilience against node capture, the threshold value for group key scheme shall be set as per the security level desired by the application and that provided by pairwise scheme.

B. Enhanced Scheme for Multiple Sessions

The above baseline scheme can be readily extended to distribute group keys for multiple sessions. For this, a distinct masking polynomial $h_j(x)$ for each session j shall be randomly selected and $h_j(i)$ for all the sessions shall be securely deployed to node i. This requirement can be intuitively reasoned as follows. Suppose that a fixed masking polynomial $h'(x)$ and a fixed concealing polynomial $l(x)$ is employed through multiple sessions. For session j, node u, by gaining node v's trust, possesses the following knowledge of node v.

$$\begin{aligned} f_j(v) &= \frac{w_j(v) - h'(v)}{g_j(v)} && (1) \\ s_j(v) &= f_j(v) + l(v) && (2) \end{aligned}$$

There are three unknowns to u, namely $h'(v)$, $f_j(v)$, and $l(v)$. As there are only two equations, node v's personal secrets are secure. However, as time evolves, more information about v will be revealed to u in the succeeding sessions if the trust relationship persists. For example, in session $(j+1)$, node u will obtain the following knowledge.

$$\begin{aligned} f_{j+1}(v) &= \frac{w_{j+1}(v) - h'(v)}{g_{j+1}(v)} && (3) \\ s_{j+1}(v) &= f_{j+1}(v) + l(v) && (4) \end{aligned}$$

Combining Equations (1) to (4), we have only four unknowns in $h'(v)$, $f_j(v)$, $f_{j+1}(v)$, and $l(v)$ while with four equations. Therefore, node u can easily derive all secrets of node v.

We observe that the concealing secret for node i can remain fixed through multiple sessions, if $h_j(x)$ is randomly chosen in each session. Equivalently, we can employ distinct concealing polynomial $l_j(x)$ for each session j and fix the masking polynomial $h_j(x)$. Regardless, in this scheme, a node can only learn information about that particular session about others and no information about different sessions is revealed. Therefore, it also provides t-revocation capability in each session.

For this multiple-session scheme, in the setup stage, a node needs to store its concealing secret and personal secrets for each session. By assuming the total targeted number of sessions to be m, we have the total memory requirement as $(m+1)\log(q)$. The broadcast message consists of a set of ID's of revoked nodes and a $2t$ degree polynomial. Therefore, the communication overhead involved is $O(mt\log(q))$. During the local collaboration phase, the communication overhead involves the exchange of t shares for a particular node whose overhead is on the order of $O(\log(q))$. These numbers, indeed, are not appealing in particular given that m can be large for long lived sensor networks. Furthermore, the above scheme lacks the self-healing capability that can accommodate occasional loss of the broadcast messages from the sink. In the remainder of this section, we will design respective enhancements that will provide self-healing capability and reduce communication overhead. In the next section, we will detail a self-evolving scheme that avoids the memory overhead for storing distinct personal secret for each session.

C. Self-healing

As the wireless medium is characterized by its lossy nature, reliable communication cannot be assumed in the key management scheme. It then becomes increasingly important to provide ways by which the sensor nodes can determine the group key even in the presence of lost broadcast messages from the sink.

In this subsection, we provide an enhancement with self-healing capability based on the design presented in [9]. The key idea of self-healing is to split the secrets into the broadcasts in multiple sessions. Therefore, even though a few broadcast messages may be missed by a particular node, the sensor node can combine those messages received to reconstruct the secret in the sessions where losses occur.

For ease of understanding, the details of the self-healing scheme is described below.

Self-healing Scheme for Multiple Sessions:

Setup:

The setup phase is similar to the baseline scheme except that we split the secret shares for each node across the targeted number of sessions denoted by m. Specifically, we divide the secret polynomial into two parts for each session i such that $f_i(x) = c_i(x) + b_i(x)$. Formally speaking, the sink selects m random t-degree polynomial $\{c_1(x), c_2(x), \cdots, c_m(x)\}$ from the finite field and then constructs $b_i(x) = f_i(x) - c_i(x)$. The sink also randomly picks $m(m+1)$ broadcast masking polynomials $h_{i,j}(x)$ of degree $2t$ from the finite field F_q and securely communicates to node v the value $\{h_{i,j}(v)\}_{i=1,2,\cdots,m,j=1,2,\cdots,m+1}$.

Broadcast:

For session j, given a set $R = \{r_i\}$, $|R| = w \leq t$, of the identities of compromised nodes known to the sink, the broadcast message B to distribute personal keys via t degree polynomial $f(x)$ to non-revoked nodes is constructed as $B = \{R\} \cup \{w_i(x) = g(x)c_i(x) + h_{j,i}(x)\}_{i=1,2,\cdots,j} \cup \{w'_i(x) = g(x)b_i(x) + h_{j,i}(x)\}_{i=j,j+1,\cdots,m}$, where the revocation polynomial $g(x)$ is constructed as $g(x) = (x - r_1)(x - r_2) \cdots (x - r_w)$.

Personal Key Recovery:

Upon receiving the broadcast message, any non-revoked node u can evaluate $w_j(x)$ and $w'_j(x)$ at point u and derive its partial personal secret shares as $c_j(u) = \frac{w_j(u)-h_{j,i}(u)}{g(u)}$ and $b_j(u) = \frac{w'_j(u)-h_{j,i}(u)}{g(u)}$. On the contrary, any revoked node v will be incapable of obtaining a new personal secret as $g(v) = 0$ and $h(u)$ is personal secret only known to node u. Secret key for session j is $f_j(u) = c_j(u) + b_j(u)$. Node u shall store all the items in $\{c_1(u), \cdots, c_{j-1}(u), b_{j+1}(u), \cdots, b_m(u)\}$ that it has not obtained yet as a result of previously lost messages.

Self-healing:

The key idea for self-healing is to allow a sensor in the network who does not receive broadcast messages in a particular session, to be able to recover the session secret on its own. If a sensor in the network receives broadcast messages for sessions j_1 and j_2, where $j_1 < j_2$, but does not receive broadcast messages for sessions between j_1 and j_2 (say $j_1 < j < j_2$), it will still be able to compute its secret for session j by recovering the partial shares $c_j(u)$ and $b_j(i)$ from sessions j_1 and j_2 respectively and then compute $f_j(u) = c_j(u) + b_j(u)$.

D. Dynamic Adjustment of the Degree of Local Collaboration

During the local collaboration phase of the above schemes, a node needs to obtain t concealed secrets from other nodes in order to construct the group key for each session. This may not be desirable dependent on the network condition. For example, when the sensors are just deployed, the number of compromised nodes is expected to be low. During this stage, requiring a node to gain t nodes' trust may be unnecessary as it may incur additional communication overhead. Instead, a smaller number of nodes collaboratively shall be able to derive the session key. Only as time evolves when more and more number of nodes are compromised, the requirement on the number of trusts shall be maximized in order to prevent the collusion of compromised nodes from destroying the network.

The proposed scheme can be readily enhanced to incorporate this capability of dynamic adjustment for reduction in communication. Instead of only broadcasting the polynomials for a node to derive its personal key, the sink can also broadcast some points on the polynomial $f_j(x) + l_j(x)$ in session j. For example, if the sink deems that k, $k \leq t$, nodes' trust shall enable a node to possesses the session key, in the broadcast message, the sink can include $(t-k)$ values of $f_j(x) + l_j(x)$ and the corresponding evaluation points (which shall not have been used as node IDs in the network). This way, a node only needs to obtain k additional concealed secrets from other nodes by local collaboration.

IV. Self-evolving Based on Decision Diffie-Hellman Problem

Obviously the schemes described in the previous section require a large amount of memory for storing the personal secrets on each sensor node for multiple sessions. For a long lived sensor network, it may be unrealistic to implement such a strategy. In this section, we propose a new scheme that allows sensor nodes to advance their personal keys from session to session and hence avoid the requirement for storing pre-deployed personal keys for each session. Due to the self-evolving construction and local collaboration, the scheme is computationally secure as compared to unconditionally secure of the aforementioned schemes.

Our scheme is based on the well known Decision Diffie-Hellman (DDH) problem [21]. Loosely speaking, given a finite cyclic group G with generator β, the DDH assumption states that no efficient algorithm can distinguish two distributions $\{\beta^a, \beta^b, \beta^{ab}\}$ and $\{\beta^a, \beta^b, \beta^c\}$ where a, b, and c are randomly chosen in $[1, |G|]$. For groups of large prime order, DDH is deemed intractable.

Although it has been the general perception that public key cryptography is not suitable for resource constraint environments typified by sensor nodes, principally owing to its complexity, recent results on key management in sensor networks have demonstrated that indeed public key schemes are feasible for sensor networks, provided that efficient algorithms, proper parameters, and hardware assistance are carefully chosen and optimized [22]. In the later part of this section, we will provide detailed discussion about the complexity of our proposed algorithm in comparison with those studied in [22–24]. Our conclusion is that the proposed scheme is feasible for sensor networks as well. Before being involved in the detailed discussion regarding this, we first present the design of this self-evolving scheme.

A. Self Evolving Scheme

As detailed in the previous Section, a fixed masking polynomial for all the sessions is not secure. The same conclusion can be drawn if simple transformation of the personal secrets is employed from session to session. For example, if a d degree polynomial $T(x)$ is used to transform $h_j(i)$ into $h_{j+1}(i)$, after d sessions of trust relationship, the trusted node will possess enough knowledge to derive the personal secrets of the trusting nodes.

Based on the assumption that DDH is a hard problem, below we describe a transformation that indeed can guarantee the security throughout multiple sessions. In other words, although we only pre-deploy an initial personal secret $h(i)$ to sensor node i and $h_j(i)$ will be derived from $h(i)$, it is computationally infeasible for a receiver to derive the senders' personal secrets after multiple sessions. The construction of the scheme based on DDH is detailed below.

Self-evolving Scheme:

Setup:

The sink selects a generator β of a subgroup $Z_p \subseteq F_q^*$ and then randomly chooses a $2t$ degree masking polynomials $h(x) \in Z_p(x)$ where $h(x) = a_0 + a_1 x + \cdots + a_{2t} x^{2t}$. Correspondingly, sensor node i obtains personal secret $h(i)$. At the same time, a concealing polynomial $l(x)$ of degree t is also selected by the sink and node i is assigned concealing secret $\beta^{l(i)}$. We remark that $h(i)$ and $\beta^{l(i)}$ shall be pre-deployed or distributed via secure channels between the sink and each node.

Evolve Personal Secret:

In session j, the sink randomly selects an integer $v_j \in Z_q^*$ and broadcasts β^{v_j}. Upon the reception of this broadcast, a node i shall evolve its personal secret by following $h_j(i) = \beta^{v_j h(i)}$.

Broadcast:

Given a set $R = \{r_i\}$, $|R| = w \leq t$, of the identities of compromised nodes known to the sink, the broadcast message B to distribute personal keys via t degree polynomial $f_j(x)$ to non-revoked nodes is constructed as $B = \{R\} \cup \{w(x) = \beta^{g(x) f_j(x) + v_j h(x)}\}$, where the revocation polynomial $g(x)$ is constructed as $g(x) = (x - r_1)(x - r_2) \cdots (x - r_w)$. Here the notation $\beta^{f(x)} = \beta^{a_0} x + \beta^{a_1} x + \cdots + \beta^{a_t} x$ if $f(x) = a_0 x + a_1 x + \cdots + a_t x$.

Personal Key Recovery:

Upon receiving the broadcast message, any non-revoked node i can evaluate $w(x)$ at point i and derive its personal key as $\beta^{g(i) f_j(i)} = \frac{w(i)}{\beta^{v_j h(i)}}$. On the contrary, any revoked node v will be incapable of obtaining a new personal secret as $g(v) = 0$ and $h(i)$ is personal secret only known to node i.

Local Collaboration:

To derive the group key, node u shall seek assistance from t fellow nodes. Towards this end, it shall broadcast this request to its neighbors. Upon the reception of this request, node i, willing to trust u, shall send a *concealed personal key* $\beta^{s(i)}$ to node u. $\beta^{s(i)}$ is constructed as $\beta^{s(i)} = \beta^{g(i) f_j(i)} \cdot \beta^{l(i)} = \beta^{g(i) f_j(i) + l(i)}$. Note the communication from i to u for conveying this concealed secret shall be confidential, which can be achieved by employing the aforementioned pairwise key scheme in the network.

Group Key Recovery:

If node u is successful in obtaining t nodes' trusts and hence their concealed secrets, it can derive the current group key by following the threshold secret sharing scheme proposed by Shamir using the Lagrange interpolation in the exponential domain. Specifically, it can compute the group key as $K = \beta^{s(0)} = \prod_{k=0}^{t} \left(\beta^{s(v_k)}\right)^{(\Lambda_k)}$ where Λ_k are the lagrange coefficients that depends on the node ID's x_i's, i.e., $\Lambda_k = \prod_{k \neq i} \frac{x_k}{x_k - x_i}$. Notice that the concealed secret $\beta^{s(i)}$ is a point on the polynomial $\beta^{s(x)} = \beta^{g(x) f(x) + l(x)}$. By interpolating t points on the same polynomial, node u can evaluate $\beta^{s(0)} = \beta^{g(0) f(0) + l(0)}$ and hence derive the group key.

We remark that the enhancements of dynamic adjustment on the number of nodes to be involved in the local collaboration can be readily applied here. So is self-healing. We omit them in our description for simplification.

B. Security Analysis

It is shown that the Diffie-Hellmen based scheme given by Naor and Pinkas [25] is secure up to t revoked users. They prove that even if t users were not revoked in polynomially many sessions, any attempt to reveal information on the shared secret at the current session involves the solution of a problem that is at least as hard as DDH. We follow the same guidelines and prove that our self evolving scheme is secure computationally. In particular, we show that information obtained in one session of a particular node by compromised nodes is not useful in the sessions to follow. The self-evolving scheme is secure against t revoked user in the sense, even if t user collude (with all their knowledge from previous sessions gained from other nodes and the sink), it is computationally infeasible for them to determine the personal secret of an non revoked user.

Let us assume by contradiction, that there exists an algorithm such that coalition of revoked users can distinguish between $\beta^{v_\alpha(h(i))}$ and a random value. If the revoked users are able to determine personal secrets for non-revoked nodes, then there exists a DDH oracle. Considering that coalition of revoked users run an algorithm A that receives as input polynomially many tuples, $(\beta^{v_\delta}, \beta^{v_\delta(h(1))}, \cdots, \beta^{v_\delta(h(t))}, \cdots, \beta^{v_\delta(h(2t))})$ and a challenge: $(\beta^{v_\alpha}, \beta^{v_\alpha(h(1))}, \cdots, \beta^{v_\alpha(h(2t))}, \gamma)$. As mentioned above if the algorithm has an non-negligible advantage in determining whether $\gamma = \beta^{v_\alpha(h(i))}$ or a random element of Z_p then it is successful.

Next, using algorithm A we construct an algorithm B that breaks the DDH assumption. B works as follows:

1) B generates a random v_δ and values to correspond $h(1), \cdots, h(2t)$. Notice that many v_δ's can be generated corresponding to different sessions.
2) It determines the values $\beta^{h(1)}, \cdots, \beta^{h(2t)}$. It also determines a value $\beta^{a(h(i))}$ denoted as τ from the challenge associated with the DDH problem.
3) After generating all the above tuples, B inputs to A the tuples $(\beta^{v_\delta}, \beta^{v_\delta(h(1))}, \cdots, \beta^{v_\delta(h(2t))})$ for all δ and the challenge $(\beta^{v_a}, \beta^{v_a(h(1))}, \cdots, \beta^{v_a(h(2t))}, \tau)$. It outputs the answer provided by A.

Algorithm A returns TRUE if it decides that $\tau = \beta^{v_a(h(i))}$ and FALSE otherwise. A TRUE returned by the algorithm shows that $\beta^{f(x)} = (\beta^{b_1}, \cdots, \beta^{b_{2t+1}})$ agrees with $\beta^{a(h(x))}$

at $x = i$. This implies that $f(i) \equiv a(h(i)) \mod p$. There are $p^{(2t)}$ such polynomials of degree $2t$, of which only one of them is $a(h(i))$. The probability that a randomly chosen polynomial, different from $h(x)$, agrees with $h(i)$ is $\frac{p^{2t}-1}{p^{2t+1}} < \frac{1}{p}$. The advantage of B is at least $1 - \frac{1}{p}$ times the advantage of A. Thus B's success probability in breaking the DDH assumption is the same as A's probability of breaking the revocation scheme.

Note that, collation of personal secrets by $(t + 1)$ nodes, given that t nodes are revoked in the current broadcast and hence whose personal secrets are disclosed, would reveal the broadcast masking polynomial. These nodes would be able to retrieve session keys for the entire network lifetime.

C. Complexity Analysis

It is generally believed that DDH is a hard problem which renders our scheme computationally secure. However, computation requirement on a sensor node in the self-evolving scheme is also much higher than the schemes mentioned in the previous section. Therefore, our focus is rather not to argue whether DDH is hard here, but to show that it is computationally feasible to implement it on a resource constrained sensor node.

Although it has been a general perception that public key systems are too complex for sensor networks, surprisingly, recent research efforts have shown that public key schemes are indeed feasible. TinyPK [23] provides an example to implement public key technology in sensor networks. It shows that sensor networks can employ RSA as the key management scheme for authenticating nodes and distributing key information. Key exchange between nodes is achieved via the Diffie-Hellman (DH) scheme which actually requires two exponentiation operations. In comparison, our scheme based on DDH requires only one exponentiation operation for the key derivation on a sensor node. Therefore, our scheme consumes even less computation power and energy than TinyPK which actually is shown to be feasible for sensor networks.

More recently, in the best paper of Percom'05 [24], the authors show that public key cryptography is viable on constrained platforms even if implemented in software. The authors provide detailed energy analysis for two public key systems, namely RSA and ECC. The results show that energy consumption for such schemes is actually surprisingly small which can be supported by a single battery throughout the life time of a node and hence can be utilized in wireless sensor networks. Notably, recent work in [22], studies the use of two different types of public key crypto-systems in sensor networks, namely Rabin's scheme [26] and NtruEncrypt algorithm [27] whose encryption complexity is on the order of $O(n^2)$ as compared to $O(n^3)$ for RSA. The conclusions there are that these two schemes can be employed on low powered devices such as sensor as long as the system is carefully optimized.

Indeed, DDH has comparable or lower complexity than the schemes studied in [22–24]. Their results validate that our proposed self-evolving scheme can be a feasible solution for key management in sensor networks with low communication and memory requirement.

V. Related Work

Group key management schemes have long attracted intensive research interests from the literature. The most naive approach for group key management is the master key approach in which there is one master key pre-deployed in each node. This approach is memory efficient, but has very poor security and key redistribution is difficult. Another approach [14] is the pairwise approach in which the central server or group controller maintains a pairwise key with each node and distributes the group key via unicast to each node, this approach is very secure but communication and memory overhead is intolerable for wireless sensor networks and scalability is also an obstacle difficult to overcome.

Advanced group key management techniques based on multicast have be broadly proposed. In [15, 16], the authors presented a protocol in which every join/leave operation in a group of size n involves $2\log_2^n$ rekey messages. An improvement was proposed in [17] by using pseudorandom generator which reduced the number of rekey messages to $\log_2^n$. In contrast to the centralized schemes, a set of distributive approaches have also been proposed [28]. In these schemes, the secret can be distributed via a broadcast to a predetermined set of users in the network which in turn will spread the information [29]. However, the scheme does not scale well as the cost increases linearly with increase in group size. At the same time, distributed schemes require redistribution of the shares as the network size increases which will incur significant communication overhead [30]. Regardless, the above schemes are proposed for wireline networks where communication and computation is not a severe constraint and thus are not applicable in sensor networks.

In ad-hoc networks, certificate authority (CA) is adopted to validate the authenticity of public keys [31]. Partially distributed CA or fully distributed CA are both discussed in [31]. In the fully distributed scheme, capabilities of CA are distributed to all the nodes in the network. After bootstrapping, a subsequent node entering the network is provided its share by k existing nodes. The k partial shares received by the new node can be utilized to construct its own share. While the concept of collaboration is similar to ours, the design and application of the collaboration is dramatically different.

Perhaps the most seminal work regarding group communication in sensor networks was presented in [8]. Unfortunately the authors served only an efficient protocol for broadcast authentication while confidentiality is left unaddressed. A group key construction scheme based on collaboration is presented in [32]. There, the knowledge possessed by a node is disseminated to the neighbors during the bootstrapping phase. During the normal operation, a node shall rely on the assistance of neighboring nodes to reconstruct group keys for different sessions. The idea is different from ours where the construction of the secret polynomials is done via the sink and hence true broadcast based key distribution can be achieved.

Finally, while our work is based on [9, 10], the introduction of the local collaboration concept has achieved various benefits notably including faster response to compromised nodes.

VI. Conclusion

In this paper, we propose a group key management scheme for wireless sensor networks based on true broadcast. By introducing the concept of local collaboration into the group key recovering process, the approach promises fast response to the ever changing network condition as sensor nodes themselves are empowered to exclude a compromised node. Various enhancements of the basic scheme provide significant reduction in the requirement of communication and memory. Notably, the self-evolving scheme avoid the requirement of pre-deploying personal secret for each session and hence can be utilized for network with extended lifetime.

As ongoing efforts, we are implementing the scheme in real sensor platforms and studying its performance. As our future work, we plan to investigate the effect of different pairwise key management schemes on the performance of the proposed group key management in detail.

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