MOBILE SECRET KEY DISTRIBUTION WITH NETWORK CODING *

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Abstract: We consider the problem of secret key distribution in a sensor network with multiple scattered sensor nodes and a mobile device that can be used to bootstrap the network. Our main contribution is a practical scheme that relies on network coding to provide a robust and low-complexity solution for sharing secret keys among sensor nodes. In spite of its role as a key enabler for this approach, the mobile node only has access to encrypted version of the keys. In contrast with probabilistic key pre-distribution schemes our method assures secure connectivity with probability one, requiring only a modest amount of memory — initially each sensor node stores only one key per secured link.

1 INTRODUCTION

Among the many security challenges posed by wireless sensor networks (WSNs), i.e. self-organizing collections of sensing devices with processing and communication capabilities, the generation and distribution of private keys for authentication and confidentiality in pairwise or group communication is arguably one of the most fundamental problems.

Currently available proposals can be divided into at least three basic types of secret key distribution schemes (Du et al., 2005): (a) trusted third party, (b) public-key infrastructure and (c) key pre-distribution. Trusted party schemes, e.g. SPINS (Perrig et al., 2002), assume that a base station provides the sensor nodes with secret keys that are encrypted with one individual key per sensor node. Although public-key infrastructure schemes have been implemented successfully in some sensor networks (Malan et al., 2004), their demands in terms of processing and communication overhead are arguably too high, in particular with respect to the power constraints imposed on this type of devices. Key pre-distribution thus emerges as a strong candidate, mainly because it requires considerably less resources. The concept is elaborated in (Eschenauer and Gligor, 2002), where a random pool of keys P is selected from the key space prior to sensor node deployment. Then, each node receives a key ring, consisting of randomly chosen k keys from P. A secure link is said to exist between two neighboring sensor nodes, if they share a key with which communication may be initiated. A random graph analysis in (Eschenauer and Gligor, 2002) shows that shared-key connectivity can be achieved almost surely, provided that each sensor node is loaded with 250 keys drawn out of a pool of roughly 100.000 sequences.

Using a different scheme with pre-installed key rings, LEAP (Zhu et al., 2003) erases the network key immediately after the pairwise keys are established. Since nodes in that situation can no longer establish pairwise keys, this protocol is only suitable for static WSNs.

In the spirit of the *Resurrecting Duckling* paradigm in ubiquitous computing (Stajano and Anderson, 1999; Stajano, 2002), we consider the scenario in which a mobile node, e.g. a handheld device or a laptop computer, is used to activate the network and help establish secure connections between the sensor nodes. We shall show that by exploiting the benefits of network coding (Fragouli et al., 2006; Deb et al., 2005), as illustrated in Fig. 1, it is possible to

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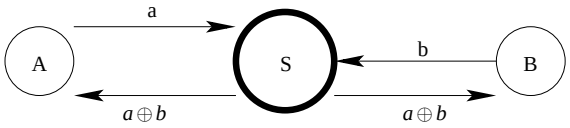


Figure 1: A typical wireless network coding example. To exchange messages a and b, nodes A and B must route their packets through node S. Clearly, a traditional scheme would require four transmissions. However, if S is allowed to perform network coding with simple XOR operations, $a \oplus b$ can be sent in one single broadcast transmission (instead one transmission with a followed by another one with b). By combining the received data with the stored message, A which possesses a can recover b and B can recover a using b. Thus, network coding saves one transmission.

design power-efficient key distribution schemes that are not probabilistic, while ensuring that the aforementioned mobile node does not constitute a single point of attack — its capture does not compromise the whole network.

Our main contribution is a practical secret key distribution scheme with efficient use of resources — in addition to a small number of transmissions and low-complexity processing (mainly XOR operations), each node is only required to pre-store a small number of keys (as many as its expected number of links). Another feature of our approach is a "blind" key distribution — although the mobile node only has access to encrypted versions of the secret keys, it is capable of using network coding to ensure that each pair of sensor nodes receives enough data to agree on a pair of secret keys.

The rest of the paper is organized as follows. Section 2 provides a detailed description of our secret key distribution scheme. Section 3 then elaborates the attacker model and proves that the mobile node is indeed ignorant about the pre-stored keys. The paper concludes with Section 4.

2 MOBILE SECRET KEY DISTRIBUTION

2.1 Key Distribution Scheme

Suppose that sensor nodes A and B want to establish a secure link via a mobile node S. Although A and B own different keys that are unknown to S, the latter is capable of providing A and B with enough information for them to recover each other's keys based on their own pre-stored keys. The basic scheme for multiple nodes, which is illustrated in Fig. 2, can be summarized in the following tasks:

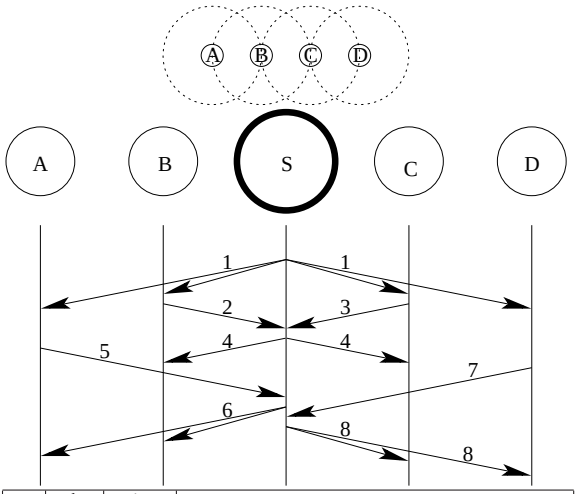
(i) *Prior to sensor node deployment*:

- Generate a large pool $\mathcal{P}$ of statistically independent keys K_i and their identifiers $i \in \{0,...,|\mathcal{P}|-1\}$; for simplicity, each global key identifier i is assumed to result from the concatenation of a node identifier n and a local key identifier j (e.g. $|n| = 24$ bit and $|j| = 8$ bit);
- Produce a one-time pad R, i.e. a binary sequence of size equal to the key size and consisting of bits drawn randomly according to a *Bernoulli* ($\frac{1}{2}$) distribution;
- Store in the memory of S a list with all identifiers i and an encrypted version of the corresponding key $K_i \oplus R$ (it shall be argued in Section 3 that in this case it is perfectly safe to use the same one-time pad R for all the keys, because they are drawn uniformly at random);
- Let $C \ll |\mathcal{P}|$ be the expected number of links that each node intends to use during its lifetime; load C keys into the memory of each sensor; each sensor node knows both its own identifier n and the local key identifiers j.

(ii) *After sensor node deployment*:

1. The sensor nodes perform standard neighborhood discovery by broadcasting their identifiers n and storing in a list L_n the identifiers announced by their neighbors;
2. S broadcasts HELLO messages that are received by any sensor node within wireless transmission range. Each sensor node sends a reply message containing $\{n, L_n\}$;
3. Upon receiving $\{n(A), L_{n(A)}\}$ from a node A and $\{n(B), L_{n(B)}\}$ from a node B, the mobile node S checks whether $n(A) \in L_{n(B)}$ and $n(B) \in L_{n(A)}$. If this is the case, S performs a simple table look-up and runs a XOR network coding operation over the corresponding protected keys, i.e. $K_{i(A)} \oplus R \oplus K_{i(B)} \oplus R$. Since R cancels out, S sends back $\{n(A) * j(A), n(B) * j(B), K_{n(A)*j(A)} \oplus K_{n(B)*j(B)}\}$, where $(n(\cdot) * j(\cdot))$ denotes the concatenation of node and local key identifiers; the local key identifier j (for each node) is initially set at 0 and increases with the number of established links;
4. Based on the received XOR combination $K_{n(A)*j(A)} \oplus K_{n(B)*j(B)}$, A and B can easily recover each other's key by performing an XOR operation using the lowest local key identifier that corresponds to an unused key (A knows $K_{n(A)*j(A)}$ and computes $K_{n(A)*j(A)} \oplus K_{n(A)*j(A)} \oplus K_{n(B)*j(B)}$, thus obtaining $K_{n(B)*j(B)}$; B proceeds similarly).

Thus, each pair of nodes shares a pair of keys which is kept secret from S.



msg	sender	receiver	content
1	S	A,B,C,D	HELLO
2	B	S	$\{n(B),[n(A),n(C)]\}$
3	C	S	$\{n(C),[n(B),n(D)]\}$
4	S	B,C	$\{n(B)*j(B),n(C)*j(C),K_{n(B)*j(B)} \oplus K_{n(C)*j(C)}\}$
5	A	S	$\{n(A),[n(B)]\}$
6	S	A,B	$\{n(A)*j(A),n(B)*(j(B)+1),K_{n(A)*j(A)} \oplus K_{n(B)*(j(B)+1)}\}$
7	D	S	$\{n(D),[n(C)]\}$
8	S	C,D	$\{n(C)*(j(C)+1),n(D)*j(D),K_{n(C)*(j(C)+1)} \oplus K_{n(D)*j(D)}\}$

Figure 2: Example of the general key distribution scheme for the topology shown above. Sensor nodes *A*, *B*, *C* and *D* want to exchange keys with their neighbors via a mobile node *S*. Initially, the nodes exchange their identifiers and wait for an HELLO message from *S* (transmission 1). After this step, each node sends a key request message to the mobile node (transmissions 2,3,5,7) and waits for the latter to send back a key reply message (transmissions 4,6,8).

2.2 Usage of Keys

There are several ways to make use of the established pair of keys. One alternative to the solution in which each node encrypts messages with its own pre-stored key and decrypts received messages with the neighbor's key, is to combine the two keys into a single key through a boolean operation (e.g. or, and). Another solution would be to encrypt the messages in a double cypher using both keys, but this option requires higher processing capability.

Perhaps the most effective option would be for the nodes to use the two shared keys (one in each direction) to agree on a session key (e.g., node *A* generates a random value *a*, encrypts it using one of the shared keys and sends it to node *B*, which generates a random value *b* and sends it back to *A*, encrypted with the other key). The main advantage is that the sensor nodes can secure their communications using the concatenation of the exchanged random values (ordered by the key identifiers by which they were encrypted), resulting in a shared key with double the size and a considerable improvement in terms of security. Naturally, the availability of suitable random number generators is a relevant issue to be taken under consideration.

3 SECURITY PERFORMANCE EVALUATION

3.1 Attacker Model

We assume two types of threats in our scheme: (1) a passive attacker that listens to all the traffic over the wireless medium and (2) an active attacker who is able to inject bogus data in the network. We assume that the attacker can gain access to the memory of the mobile node or to the memory of a limited number of sensor nodes, but never to both. We consider that the adversary computational resources are limited (polynomial in the security parameter).

The first type of attacker does not constitute a threat because the keys cannot be decoded from the XOR messages in the ether. The second type of attack can be detected by the legitimate nodes, who ignore any messages that are corrupted by an invalid key.

3.2 One-Time Pad Security

The keys stored in the mobile node are protected by a one-time pad. It is well-known that the one-time pad can be proven to be perfectly secure for any message statistics if the key is (a) truly random, (b) never reused and (c) kept secret. In our case, the messages correspond to keys drawn from a uniform distribution and, consequently, the requirement that the one-time pad is never re-used can be dropped, as stated in the following theorem.

Theorem 3.1 *The knowledge of* $\{K_1 \oplus R, K_2 \oplus R, ..., K_m \oplus R\}$ *does not increase the information that the attacker has about any key, i.e.,* $\forall i \in \{1,...,m\}$,

$$P(K_i = x | K_1 \oplus R = y_1, ..., K_m \oplus R = y_m) = P(K_i = x).$$

Sketch of proof First, notice that $P(K_i = x) = \frac{1}{2^n}$. We shall prove that $P(K_i = x | K_1 \oplus R = y_1, ..., K_m \oplus R = y_m) = \frac{1}{2^n}, \forall i \in \{1,...,m\}$, which yields the result.

$$\begin{aligned} & P(K_i = x | K_1 \oplus R = y_1, ..., K_m \oplus R = y_m) \\ = \; & P(K_i = x | K_1 \oplus K_i = y_1 \oplus y_i, ..., K_m \oplus K_i = y_m \oplus y_i), \end{aligned}$$

where the event $K_i \oplus K_i = y_i \oplus y_i$ is not present, because it is redundant. Let $z_j = y_j \oplus y_i$, for $1 \leq j \leq m$ and $j \neq i$. Let A denote the event $\{K_i = x\}$ and B denote the event $\{K_1 \oplus K_i = z_1, ..., K_m \oplus K_i = z_m\}$. Then, $P(K_i = x | K_1 \oplus K_i = z_1, ..., K_m \oplus K_i = z_m) = P(A|B)$.

We already have seen that $P(A) = P(K_i = x) = 1/2^n$. We have that:

$$\begin{aligned} P(B|A) &= P(K_1 \oplus K_i = z_1, ..., K_m \oplus K_i = z_m | K_i = x) \\ &= \prod_{j=1}^{m} P(K_j = z_j \oplus x) = \frac{1}{2^{n(m-1)}} \end{aligned}$$

$$\begin{aligned} P(B) &= P(K_1 \oplus K_i = z_1, ..., K_m \oplus K_i = Z_m) \\ &= \prod_{j=1}^{m} P(K_j \oplus K_i = z_j) = \frac{1}{2^{n(m-1)}} \end{aligned}$$

Therefore, we have that $P(A|B) = \frac{\frac{1}{2^{n(m-1)}} \cdot \frac{1}{2^n}}{\frac{1}{2^{n(m-1)}}}$. ∎

3.3 Memory Requirements

We recall that each node n has C keys K_i in memory, each one identified by $|i| = |n| + |j|$ bits, where $|\cdot|$ denotes the size of the argument. To store the protocol data, each node requires $|n| + C * (|j| + |K_i|)$ bits of memory space and the mobile node needs $2^{|i|} * (|i| + |K_i|) = |\mathcal{P}| * (\lceil log_2(|\mathcal{P}|) \rceil + |K_i|)$ bits. For example, if we assign $n = 24$ there is space for 16.777.216 different node identifiers. For $j = 8$, each sensor node can obtain 256 keys (e.g. if each node initially has $C = 20$ keys in its memory, there is space for 246 extra keys). Table 1 illustrates the required resources, which we deem very reasonable under current technology.

Table 1: Required memory for each sensor node (*SN*) and required memory for the mobile node (*MN*), for fixed values of $n = 24$, $j = 8$ and $C = 20$.

$\|K_i\|$	Size on *SN*	Size on *MN*
128 bit	343 Bytes	80.0 GB
64 bit	183 Bytes	48.0 GB
32 bit	103 Bytes	32.0 GB

We omit the details of our implementation on TelosB motes due to lack of space.

4 CONCLUSIONS

We presented a secret key distribution scheme for large sensor networks. Unlike (Eschenauer and Gligor, 2002) and (Du et al., 2005), this is *not* a probabilistic scheme, i.e. any two nodes that can reach each other can communicate securely with probability one, using a small number of pre-stored keys and without the need for establishing path-keys albeit at the expense of a mobile node for bootstrapping. Since our protocol and its extensions can easily accommodate for additional nodes, new keys and secured links, we deem the proposed network coding approach to be well suited for dynamic sensor networks with stringent memory and processing restrictions. Extensions for group keys, extra keys request and revocation can be implemented and will be reported elsewhere.

Although our use of network coding was limited to XOR operations, more powerful schemes are likely to result from using linear combinations of the stored keys. Investigating the potential of random linear network coding (Lima et al., 2007) in the context of secret key distribution is one of the main objectives of our ongoing work.

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