Entity Recognition for Sensor Network Motes (Extended Abstract)

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Abstract: Message authenticity (knowing "who sent this message") is an important security issue for sensor networks, and often difficult to solve. Sometimes, it may be sufficient and more efficient to solve the simpler *entitiy recognition* problem, instead: "is the message from the same entity that sent the previous messages?". This paper describes entity recognition for sensor network motes. A protocol presented at SAC 2003 [9] is shown to be insecure, and a new and provably secure protocol is proposed.

1 Introduction

Consider the following story: Two strangers, Alice and Bob, meet at a party and make a bet. Days later, after it had turned out that Alice is the winner, Bob receives a message: "*Bob, please transfer the prize to bank account [...] Thank you. Alice.*". How does Bob know that this message actually has been sent from that person, who had called herself "Alice" at that party? In other words, how does Bob recognise a message from Alice?

In this paper, Alice and Bob are sensor network motes. Using digital signatures, would be computationally expensive for them. We present a "low-cost" solution, based on secret-key cryptography (namely cryptographic hashing and message authentication). We neither assume the existence of a trusted third party, nor the availability of pre-deployed secret or authentic information, the network topology can be dynamic, and there may be no (securely) synchronised time. Sensor networks typically have most or even all of these properties.

1.1 Prior Results

The **Guy Fawkes protocol** [1] assumes Alice to send messages to Bob, which can not be interrupted or distorted. While this appears reasonable in the original use case (Guy Fawkes would publish his commitments in a newspaper and check if they appear in print), this is clearly unreasonable for sensor networks. The **remote user authentication protocol** proposed in [7] extends the Guy Fawkes protocol by a cut-and-choose technique, which makes the protocol computationally quite expensive.

Usage of message authentication codes (MACs) is a cryptographic standard technique to authenticate messages. This requires sender and receiver to agree on a shared secret key in advance. To do so, Russell [8] proposes to **use the Diffie-Hellman key exchange** [4] at protocol initialisation. The problem here is that the key exchange requires computationally expensive public-key operations, though only during the initalisation phase. In the full paper, [6], we briefly compare this approach to our approach.

1.2 Description of the Scenario

In short, we assume Eve, the adversary, to have *full control over the connection between Alice and Bob*. We consider this to be reasonably pessimistic: Over-estimating the adversary is not as bad as under-estimating her capabilities. Thus, Eve can

- ○ read all messages sent from Alice or from Bob,
- ○ modify messages, delay them or send them multiple times to either party,
- ○ and send messages generated by herself to Alice or Bob or both.

We have to make one exception, though. Without some faithfully relayed initial messages, the entire notion of "recognition protocols" would not make sense. Thus, we assume an initial phase (typically with one message from Alice to Bob, and a second message from Bob to Alice), where Eve reads the messages, but she relays them faithfully.

Driven by reasonable pessimism as before, we assume that Eve aims for an *existential forgery* in a *chosen message* scenario:

- ○ She can choose messages x_i for Alice to authenticate and send ("commit").
- ○ She succeeds if Bob accepts any message $x' \neq x_i$ as authentic ("existential forgery").

More formally, we write commit-message(x_i,i) if Alice authenticates and sends the message x_i in time-frame i. In practice, x_i will be a value from "outside the scope of the protocol", e.g., the result of a measurement of a sensor attached to Alice. It should be anticipated that Eve has some influence on x_i, and in theory, we assume that Eve can choose x_i. We write accept-message(x_i, i), if Bob believes the message x_i to be authentic and fresh in time-frame i.[1] Eve wins if she somehow can make Alice to commit-message(x_i,i) and Bob to accept-message(x', i).

Since Eve has full control over the connection between Alice and Bob, the reliability of the connection depends on her. (In practice, there can also be non-hostile reasons for a connection to become unreliable.) Thus, *denial of service* attacks are trivial for Eve. We point out, however, that our solution is *sound* (i.e., if Eve works like a passive wire, the protocol works as intended) and supports *recoverability*: if, after some suppressed or modified messages, Eve again begins to honestly transmit all messages, like a passive wire, the soundness with respect to new messages is regained.

1.3 Security Parameters and Cryptographic Base Operations

Let c and s be security parameters. We consider s to be the size of a symmetric key and c to be the output size of a message authentication code. In a typical application scenario, we would require $s \geq 80$ and $c \geq 30$. The two building blocks in this paper are a cryptographic hash function h (which we actually use as a one-way function $h : \{0,1\}^s \rightarrow \{0,1\}^s$), and a message authentication code (in short: a "MAC") $m : \{0,1\}^s \times \{0,1\}^* \rightarrow \{0,1\}^c$. Hash functions and MACs are rather cheap to implement and evaluate. We write $x \in_{\mathrm{R}} \{0,1\}^s$ for the uniformly distributed random choice of a hash input. Finally, n is a predefined constant (the maximal number of messages to authenticate).

[1] Our notion of freshness implies some (small) time frame for each x_i, which is known to Bob. The message x_i is "fresh" in frame i, if Alice had actually committed to x_i within frame i. During a time frame, Alice only commits to one single message, and Bob accepts (at most) one such message.

2 Attacking a Proposed Solution

In [9] an entity recognition protocol is proposed (dubbed as "zero common-knowledge"). [9] even present a proof of security for that protocol. Unfortunately, the proof is flawed, and we actually have found an attack against that protocol.[2]

At first, Alice chooses a random value a_0 and generates a hash chain $a_1 := h(a_0)$, ..., $a_n := h(a_{n-1})$. Similarly, Bob chooses b_0 and generates $b_1 := h(b_0), \ldots, b_n := h(b_{n-1})$. **The initialisation phase**, where we allow Eve to read the messages, but assume Eve to relay messages faithfully, consists of two messages: Alice $\rightarrow$ Bob: a_n. Bob $\rightarrow$ Alice: b_n. After the initialisation phase, Alice's internal state can be described by the triple (b_n, n, 1), and Bob's by (a_n, n, 1). During protocol execution, we write (b_i, j, u) for Alice's internal state and (a_j, i, v) for Bob's. (The first value is the currently verified "endpoint" of the other party's hash chain, the second points into the own hash chain, and the third counts the number of necessary repetitions.) **Authenticating a text** x goes like this:

```
1. Alice $\rightarrow$ Bob: $m(a_{j-u-1}, x)$, $a_{j-1}$.
2. Bob verifies $h(a_{j-1}) = a_j$.
3. For $k := 1$ to $k' :=$ max$\{u, v\}$ do
    a) Bob $\rightarrow$ Alice: $b_{i-k}$.
    b) Alice verifies $h(b_{i-k}) = b_{i-k+1}$.
    c) Alice $\rightarrow$ Bob: $a_{j-k-1}$.
    d) Bob verifies $h(a_{j-k-1}) = a_{j-k}$.
    e) If any verification fails or the loop is interrupted,
       then (Alice and Bob abort) Alice's new internal state is ($b_i$, $j$, max$\{u, k+1\}$).
                                  Bob's new internal state is ($a_j$, $i$, max$\{v, k+1\}$).
       Else (both continue)...... Alice's new internal state is ($b_{i-k'}$, $j - k' - 1$, 1).
                                  Bob's new internal state is ($a_{j-k'}$, $i - k' - 1$, 1).
```

Let Alice's internal state be $(b_i, j, 1)$ and Bob's $(a_j, i, 1)$. The **attack** works as follows:

```
1. Alice $\rightarrow$ Bob: $m(a_{j-2}, x)$, $a_{j-1}$.
2. Bob verifies $h(a_{j-1}) = a_j$. (OK!)
3. For $k := 1$ to 1 do
    a) Bob $\rightarrow$ Alice: $b_{i-1}$.
    b) Alice verifies $h(b_{i-1}) = b_i$. (OK!)
    c) Alice $\rightarrow$ Bob: $a_{j-2}$. Manipulation: Eve changes $a_{j-2}$ to $a' \neq a_{j-2}$.
    d) Bob verifies $h(a') = a_{j-2}$. (Check fails!)
```

Thus, Alice sends a_{j-2} in Step 3.c, but Bob receives $a' \neq a_{j-2}$. Since Alice's check is OK, her internal state becomes (b_{i-1}, $j - 2$, 1). On the other hand, Bob's check fails, thus his new internal state is (a_i, j, 2). Now assume the next message x' to authenticate:

```
1'. Alice $\rightarrow$ Bob: $m(a_{j-4}, x')$, $a_{j-3}$.
2'. Bob verifies $h(a_{j-3}) = a_j$. (Check fails!)
```

At a first look, this is a denial of service attack – and a powerful one. Eve modifies a single message, and the protocol stalls, because it lacks of *recoverability*. (In fact, any random corruption of a_{j-2} is likely to break the service.) But Eve can even *forge* any message x'': To accept x'', Bob needs to see a_{j-1}, a_{j-2}, and a_{j-3}, verifying $h(a_{j-1}) = a_j$, $h(a_{j-2}) = a_{j-1}$, and $h(a_{j-3}) = a_{j-2}$. In step 1', Alice sends a_{j-3} to Bob. *Eve, having seen a_{j-3}, can impersonate Alice and convince Bob to accept any x'' of Eve's choice.*

[2] The proof in [9] implicitly assumes either party to notice when the other party rejects a message. In communication scenarios relevant for entity recognition, this is hardly realistic.

3 A Description of our Protocol

In this section, we describe a new protocol to solve the entity recognition problem without using public-key cryptography. For initialisation, Alice chooses a random value a_0 and generates a hash chain $a_1 := h(a_0)$, …, $a_n := h(a_{n-1})$. Similarly, Bob chooses b_0 and generates $b_1 := h(b_0), \ldots, b_n := h(b_{n-1})$. When running the protocol, both Alice and Bob learn some values b_i resp. a_i from the other's hash chain. If Alice accepts b_i as authentic, we write accept-key(b_i). Similarly for Bob and accept-key(a_i).

The initialisation phase, where we allow Eve to read the messages, but assume Eve to relay messages faithfully, consists of two messages:

1. Alice $\rightarrow$ Bob: a_n. (Thus: accept-key(a_n).)
2. Bob $\rightarrow$ Alice: b_n. (Thus: accept-key(b_n).)

We split the protocol up into n epochs (plus the initialisation phase). The epochs are denoted by $n-1, \ldots, 0$ (in that order). Each epoch allows Alice to send a single authenticated message, and Bob to receive and verify it. The internal state of each Alice and Bob consists of an epoch counter i, the most recent value from the other's hash chain, i.e., the value b_{i+1} for Alice, and a_{i+1} for Bob (we write accept-key(b_{i+1}), accept-key(a_{i+1})), and a one-bit flag, to select between program states A0 and A1 for Alice resp. B0 and B1 for Bob.

Also, both Alice and Bob store the root a_0 resp. b_0 of their own hash chain.[3] This value doesn't change during the execution of the protocol.

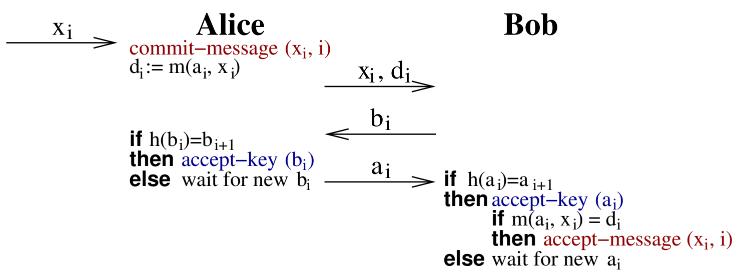
After the initial phase, and before the first epoch $n-1$, Alice's state is $i = n-1$, accept-key(b_n), and A0, and Bob's is $i = n-1$, accept-key(a_n), and B0. **One epoch** i can be described as follows:

```
A0 (Alice's initial state) Wait for $x_i$ (from the outside), then continue:
    commit-message($x_i$,$i$); compute $d_i = m(a_i, x_i)$ (using $a_i$ as the key to authenticate $x_i$);
    send $(d_i, x_i)$; goto A1.
A1 Wait for a message $b'$ (supposedly from Bob), then continue:
    if $h(b') = b_{i+1}$ then $b_i := b'$; accept-key($b_i$); send $a_i$; set $i := i - 1$; goto A0;
    else goto A1.
B0 (Bob's initial state) Wait for a message $(d_i, x_i)$, then continue: send $b_i$ and goto B1.
B1 Wait for a message $a'$ (supposedly from Alice), then continue:
    if $h(a') = a_{i+1}$
    then $a_i := a'$; accept-key($a_i$);
        if $m(a', x_i) = d_i$ then accept-message($x_i$, $i$); (authentic in epoch i)
        set $i := i - 1$; goto B0;
    else goto B1.
```

If, in state B1, Bob is sent a' with $h(a') = a_{i+1}$ but $m(a', x_i) \neq d_i$, Bob will set $i := i-1$; and go to state B0. Accordingly, no message will be accepted as "authentic in that epoch".

One epoch consists of two messages from Alice to Bob and one from Bob to Alice, see Figure 1. The protocol is **sound**: If all messages are faithfully relayed, Alice commits to the message x_i in the beginning of epoch i and Bob accepts x_i at the end of the same epoch. Also, the protocol can **recover** from message corruption: Repeating old messages can't harm security, Eve may know them, anyway. We thus allow Alice to re-send a_{i+1} and (x_i, d_i), if she is in state A1 and has been waiting too long for the value b_i from Bob.

[3] Alice needs to send hash chain values a_i. One of the advantages of a hash chain is that the values a_{i-1}, …, $a_{i-2}, \ldots$ can be used for authentication purposes, step by step. Another advantage is that Alice does not have to store *all* the values a_0, …, a_n, which would be demanding for any low-end device. Storing a_0 is sufficient, but for improved performance, Alice can implement a time-storage trade-off [3]. (Similarly for Bob and the b_i.)



x_i
Alice
Bob
commit−message (x_i, i)
$d_i := m(a_i, x_i)$
x_i, d_i
b_i
if $h(b_i)=b_{i+1}$
then accept−key (b_i)
else wait for new b_i
a_i
if $h(a_i)=a_{i+1}$
then accept−key (a_i)
if $m(a_i, x_i) = d_i$
then accept−message (x_i, i)
else wait for new a_i

Figure 1: Simplified description of one epoch of the protocol

Similarly, if Bob is in state B1 and has been waiting too long for a_i, Bob sends the value b_i again. This allows our protocol to recover.

4 Final Comments

As we demonstrated by the *attack* in Section 2, designing secure entity recognition protocols is tricky and error-prone. Thus, it is desirable to prove the security of a proposed protocol. Further, we argue that authentication and recognition protocols for sensor networks must be rather efficient to run on extremely low-cost devices and to save energy resources [10]. Our protocol

- is extremely efficient,
- does not need a trusted third party or a key pre-distribution scheme,
- and is provably secure. In the full paper [6], we **formally prove the security of our protocol**, assuming the security of the primitive operations h and m.

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