

# Concrete Security for Entity Recognition: The Jane Doe Protocol (Full Paper)

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**Abstract.** Entity recognition does not ask whether the message is from some entity  $X$ , just whether a message is from the same entity as a previous message. This turns out to be very useful for low-end devices. Motivated by an attack against a protocol presented at SAC 2003, the current paper proposes a new protocol – the “Jane Doe Protocol” –, and provides a formal proof of its concrete security. The protocol neither employs asymmetric cryptography, nor a trusted third party, nor any key pre-distribution. It is suitable for light-weight cryptographic devices such as sensor network motes and RFID tags.

## 1 Introduction

Consider the following story: Two strangers, Jane and John Doe, meet at a party and make a bet. They introduce themselves as Jane and John Doe, which may or may not be their real names (who cares at a party?). Some days later, however, it turns out that Jane is the winner, and John receives a message: “*John, please transfer the prize to bank account [...] Thank you. Jane.*”. How does John know that this message actually has been sent from that person, who had called herself “Jane” at that party? In other words, how does John recognise Jane – or a message from her?

Below, we will use the names Alice and Bob instead of Jane and John Doe for sender and receiver, in order to enhance readability for the cryptographically trained reader. As the protocol goal is about entity recognition, “real” names are unimportant. Alice and Bob are technical devices communicating in a hostile environment. Recognising each other would be easy if they could use unique identities and digital signatures: Initially, Alice would send Bob her public key. Later, Alice would sign all the messages she sends to Bob, and Bob would verify these signatures. But digital signatures are computationally expensive, and may seem an “overkill” to the problem at hand.

In this paper, we present the **Jane Doe protocol**, a light-weight solution to entity recognition using only symmetric primitives (namely, message authentication codes). Even low-end devices, which are too slow for digital signatures or the like, can run our protocol. The protocol does not depend on any trusted

third party. Neither does it require a pre-established common secret key. It runs efficiently enough for real-time applications. In addition, it is interactive and provides information about the freshness and timeliness of messages.

Our research is motivated by the emergence of extremely low-power and low-cost devices such as sensor network motes and RFID tags. The continued desire to make these devices smaller at an attractive price offsets the technological advancements of increasing computational power. While implementing digital signatures and public-key techniques on such devices is technologically feasible, it is a hard burden from an economic viewpoint. Also, such devices are often used in networks where one can neither assume availability of a trusted third party, nor availability of pre-deployed secret or authentic information, and with a dynamic network topology. Another motivation is the question to what degree one can imitate the functionality of public-key cryptography and digital signatures by just using some simple primitives from symmetric cryptography. The Jane Doe protocol turns out to be as powerful as the common two step protocol for authenticating messages, consisting of a non-authenticated Diffie-Hellman key agreement at initialisation time followed by MAC authenticated messages.

*Previous Work:* The security goal of entity recognition has independently been proposed by Arkko and Nikander [2], Weimerskirch and Westhoff [21], and Seigneur et al. [19], using names such as “temporal separation” or “zero-common-knowledge authentication”. Later, Hamell et al. [10] formalised entity recognition. Drielsma et. al. called it “sender invariance” [8].

An early protocol to actually address entity recognition was the **Resurrecting Duckling protocol** by Stajano and Anderson [20]. Since it requires the exchange of a secret key in the initialisation phase, this protocol is vulnerable to a passive adversary at this stage.

The **Guy Fawkes protocol** by Anderson et al. [1] is more suitable entity recognition, since it does not require a pre-shared key or trusted third party. It uses a one-way function  $h$ , as follows:

- Initially, Alice chooses a random<sup>1</sup> codeword  $k_0$  and sends  $h(k_0)$  to Bob.
- For each message  $x_i$  ( $i = 1, 2, \dots$ ), Alice chooses a new codeword  $k_i$  and commits to the hash value  $a_i = h(x_i, h(k_i), k_{i-1})$ .
- After  $a_i$  has been made public, Alice sends  $(x_i, h(k_i), k_{i-1})$  to Bob. He verifies whether  $a_i$  was indeed a commitment to these values, and whether  $k_{i-1}$  is indeed the codeword committed to in the last round. If both conditions are met, he accepts  $x_i$  as authentic.

This protocol implicitly assumes Alice to know when Bob has seen her commitment  $a_i$ . While this may be the case in the original use case (Guy Fawkes would publish his commitments in a newspaper), an explicit confirmation of receipt may be desirable in most application contexts.

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<sup>1</sup> In the following, “random” without further qualification always implies uniformly distributed from some finite set.

The Guy Fawkes protocol uses hash chains of length 1. In general, a **hash chain** [12] is used for authentication purposes by choosing  $k_0$ , computing  $k_1 := h(k_0)$ ,  $k_2 := h(k_1)$ ,  $\dots$ ,  $k_n := h(k_{n-1})$ , and then successively revealing  $k_n$ ,  $k_{n-1}$ ,  $\dots$ . In spite of the name “hash chain”,  $h$  does not have to be a cryptographic hash function, but a one-way function.

The **Remote User Authentication protocol** proposed by Mitchell [15] uses a message authentication code (MAC) and a cut-and-choose algorithm. The protocol could be adapted to authenticate messages instead of users, but the cut-and-choose procedure is computationally expensive. Mitchell recommends a selection of 17 out of 35 committed values, slowing down the implementation considerably compared to the Guy Fawkes protocol.

In [18], messages are authenticated using MACs, with a symmetric key being exchanged **using Diffie-Hellman key exchange** at protocol start. The problem here is that the key exchange requires public-key operations, which are too onerous for low-end systems. In appendix B, we provide a rough comparison of this approach with our proposal.

The **zero-common-knowledge protocol** [21] from SAC 2003 uses hash chains, but turned out to be flawed. The attack can be found in section 3. It also has been described in [13].

An early 5-page abstract of the current research has been published at Informatik 2005, without any proofs [13]. A longer version, including proofs, has been accepted for Indocrypt 2008 [14]. This is the full version.

*Organisation:* Section 2 introduces the world Alice, Bob and the attacker live in. Section 3 describes a protocol from SAC 2003 and demonstrates an attack against that protocol. 4 delivers a description of our protocol, which is analysed in Section 5. Conclusions are given in Section 6.

Appendix A discusses bi-directional communication. Appendix B compares the power consumption of the Jane Doe protocol with the power consumption for a scheme employing a Diffie-Hellman key exchange. Appendix C discusses a seemingly obvious generalisation of the current proposal.

## 2 Scenario Description

*Sending messages:* Alice is the sender of messages, Bob the receiver. All protocols start with an **initialisation phase**, where Alice and Bob for the first time contact each other and exchange some initial material. Later, messages are sent from Alice to Bob in distinct time frames, which we denote as **epochs**. There can be at most  $n$  such epochs. Each such epoch  $i$  consists of four basic steps:

1. Alice receives some external data  $x_i$ , the origin of which lies outside the scope of the protocol (e.g. a measurement from a sensor).
2. Alice authenticates and sends the message to Bob. Formally, we write  $CommitMessage(x_i, i)$ .
3. Bob sends a confirmation that he received some data, supposedly from Alice.

4. Alice opens the commitment and proves that it was really her who send the message. We write  $\text{AcceptMessage}(x_i, i)$  if Bob believes the message  $x_i$  to be authentic and fresh in epoch  $i$ .

*Adversary capabilities:* The well-known Dolev-Yao model [7] assumes that Eve is in full control over the connection between Alice and Bob, i.e. she is an **active adversary**. In particular, she can

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

This is considered as reasonable pessimism: Over-estimating the adversary is not as bad as under-estimating her capabilities. However, e.g. Gollmann [9] argues that novel applications may need more specific models. In our case, we make the special assumption that during the initialisation phase, Eve behaves like a **passive adversary**. She can read the messages between Alice and Bob (which precludes any kind of secret key exchange), but she relays them faithfully. Note that this is a weakening of the usual assumption that Alice and Bob can use a protected communication channel for initialisation, i.e. our scenario requires less external protection than most other proposals.

In typical application scenarios (e.g. for sensor networks), Eve may even be able to extract secret data inside the devices by tampering, in addition to controlling the network. Our protocol does not protect against this kind of threat. If this threat is relevant for the application at hand, and if it can not be mitigated by using tamper-resistant hardware, then additional protection measures (like introducing redundancy and using secure multi-party computation algorithms) have to be introduced at a higher layer of the protocol stack.

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

- Eve may have some influence on  $x_i$ . Thus, for purposes of security analysis, we allow her to choose messages  $x_i$  which Alice will authenticate and send, i.e.  $\text{CommitMessage}(x_i, i)$ .
- She succeeds if Bob accepts any message  $x' \neq x_i$  as authentic, i.e.  $\text{AcceptMessage}(x', i)$ .

At the beginning of the protocol, Alice and Bob choose initial random values  $a_0$  resp.  $b_0$ . From then on, Alice and Bob act as strictly deterministic machines. When receiving a message, Alice and Bob update their internal state and send a response, if necessary. Eve is a probabilistic machine with independent connections to Alice and to Bob. In the context of this paper, the actual choice of a machine model is not important – any reasonable machine model will do.

We require the initial random values (=keys)  $a_0$  and  $b_0$  to be chosen independently from the keys for other sessions. To this regard, our setting is much simpler than any communication scenario where *the same* key material can be used in more than one session (see e.g. [4, 3]).

*Limitation:* We assume that the number of messages to be authenticated is known in advance, or a reasonable upper bound is known. During the initialisation phase, both Alice and Bob commit to the endpoint of a hash chain. The length of this hash chain bounds the number of messages to be authenticated. This limits of our approach, compared to other solutions employing public-key cryptography. Those, however, may be less efficient than our scheme, see Section B in the appendix for evaluating the power consumption.

*Reliability:* Since Eve has full control over the connection between Alice and Bob, the reliability of the connection depends on her. Thus, *denial of service* attacks are trivial for Eve. In addition, if the communication channel itself is unreliable, messages may be lost or faulty messages may be received even without the active involvement of a malicious adversary. Such problems can not be solved at cryptographical level, but have to be managed by the network or transport layer in the protocol stack. But the following reliability properties can be guaranteed:

**Soundness:** If the network is reliable and Eve relays messages like a passive wire, the protocol works as intended: Bob accepts each message  $x_i$  Alice has committed to.

**Recoverability:** If Eve suppresses or modifies some messages, or creates some messages of her own, Bob may refuse to accept a message  $x_i$  Alice has committed to. However, once Eve begins again to honestly transmit all messages, like a passive wire, the soundness with respect to new messages is regained.

### 3 Attacking a Proposed Solution

**Attacking a Protocol from SAC 2003.** In [21], Weimerskirch and Westhoff propose an entity recognition protocol (termed *Zero Common-Knowledge*) and present a proof of security for that protocol. Unfortunately, the proof is flawed, since it implicitly assumes either party to notice when the other party rejects a message. In communication scenarios relevant for entity recognition, this is hardly realistic. In the following, we will show how this can be used for an attack. Let  $s$  be the key size and  $h : \{0, 1\}^s \rightarrow \{0, 1\}^s$  a one-way function. Typically  $s \geq 80$ , and  $h$  is a cryptographic hash function. Furthermore,  $m : \{0, 1\}^s \times \{0, 1\}^* \rightarrow \{0, 1\}^c$  is a cryptographic message authentication code (MAC) with key size  $s$  and  $c$ -bit authentication tags, typically  $32 \leq c \leq s$ .

*Initialisation:* At first, Alice chooses  $a_0 \in_R \{0, 1\}^s$  and generates a hash chain  $a_1 := h(a_0), \dots, a_n := h(a_{n-1})$ . Similarly, Bob chooses  $b_0 \in_R \{0, 1\}^s$  and generates  $b_1 := h(b_0), \dots, b_n := h(b_{n-1})$ . The initialisation phase, where Eve can read the messages but relays them faithfully, consists of sending (1) Alice  $\rightarrow$  Bob:  $a_n$  and (2) 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  $(a_n, n, 1)$ .

*Authentication:* At some point in time, we write  $(b_i, j, u)$  for Alice's internal state and  $(a_j, i, v)$  for Bob's.<sup>2</sup> Authenticating a message is achieved as follows:

1. Alice → 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 → Alice:  $b_{i-k}$ .
  - (b) Alice verifies  $h(b_{i-k}) = b_{i-k+1}$ .
  - (c) Alice → 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 stop execution:
    - i. Alice's new internal state is  $(b_i, j, \max\{u, k+1\})$ .
    - ii. Bob's new internal state is  $(a_j, i, \max\{v, k+1\})$ .
  - (f) Else (\* everything went well \*)
    - i. Alice's new internal state is  $(b_{i-k'}, j - k' - 1, 1)$ .
    - ii. Bob's new internal state is  $(a_{j-k'}, i - k' - 1, 1)$ .

*Attack:* However, this protocol is insecure. Let Alice's internal state be  $(b_i, j, 1)$  and Bob's  $(a_j, i, 1)$ .

1. Alice → 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 → Alice:  $b_{i-1}$ .
  - (b) Alice verifies  $h(b_{i-1}) = b_i$ . (OK!)
  - (c) Alice → Bob:  $a_{j-2}$ . **Eve changes  $a_{j-2}$  to  $a' \neq a_{j-2}$ .**
  - (d) Bob verifies  $h(a') = a_{j-2}$ . (Check fails!)

Since Alice's check is OK, she executes step 3(f)i, and her internal state becomes  $(b_{i-1}, j - 2, 1)$ . Bob's check fails, he executes step 3(e)ii, and his new internal state is  $(a_i, j, 2)$ . Now assume the next message  $x'$  to authenticate:

- 1'. Alice → 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.

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<sup>2</sup> The first value is the currently verified “endpoint” of the other party's hash chain, the second one points into the own hash chain, and the third value counts the number of necessary repetitions.

## 4 The Jane Doe Protocol

In this section, we describe the Jane Doe protocol to solve the entity recognition problem without using public-key cryptography. We write  $s$  for the size of a symmetric key. A second security parameter is the tag size  $c \leq s$  for message authentication. (Typically:  $s \geq 80$  and  $c \geq 32$ .) We use two functions, a MAC  $m : \{0, 1\}^s \times \{0, 1\}^* \rightarrow \{0, 1\}^c$  and a one-way function  $h : \{0, 1\}^s \rightarrow \{0, 1\}^s$ . (In Section 5, we will describe how to derive both  $m$  and  $h$  from a single MAC.) We write  $x \in_R \{0, 1\}^s$  to indicate a random  $s$ -bit string  $x$ , uniformly distributed.

*Initialisation phase:* For initialisation, Alice chooses  $a_0 \in_R \{0, 1\}^s$  and generates a hash chain  $a_1 := h(a_0), \dots, a_n := h(a_{n-1})$ . Similarly, Bob chooses  $b_0 \in_R \{0, 1\}^s$  and generates  $b_1 := h(b_0), \dots, b_n := h(b_{n-1})$ . 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  $\text{AcceptKey}(b_i)$ . Similarly for Bob and  $\text{AcceptKey}(a_i)$ . The initialisation phase, where Eve can read the messages but relays them faithfully, consists of two messages:

1. Alice  $\rightarrow$  Bob:  $a_n$ . (Thus:  $\text{AcceptKey}(a_n)$ .)
2. Bob  $\rightarrow$  Alice:  $b_n$ . (Thus:  $\text{AcceptKey}(b_n)$ .)

*Message authentication:* We split the protocol up into  $n$  epochs, plus the initialisation phase. The epochs are denoted by  $n - 1, \dots, 0$  (in that order). Each epoch allows Alice to send one authenticated message<sup>3</sup>, 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.,  $b_{i+1}$  for Alice, and  $a_{i+1}$  for Bob (we write  $\text{AcceptKey}(b_{i+1})$  and  $\text{AcceptKey}(a_{i+1})$ ), 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.<sup>4</sup> This value does not change during the execution of the protocol. Note that after the initial phase, and before the first epoch  $n - 1$ , Alice's state is  $i = n - 1$ ,  $\text{AcceptKey}(b_n)$ , and A0, and Bob's is  $i = n - 1$ ,  $\text{AcceptKey}(a_n)$ , and B0. One epoch  $i$  can be described as follows:

### A0 (Alice's initial program state)

Wait for  $x_i$  (from the outside), then  $\text{CommitMessage}(x_i, i)$ :

1. compute  $d_i = m(a_i, x_i)$  (using  $a_i$  as the key to authenticate  $x_i$ );
2. send  $(d_i, x_i)$ ; **goto** A1.

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<sup>3</sup> Several messages can be sent per epoch. For ease of presentation, we combine them.

<sup>4</sup> Alice can either store  $a_0$  and compute the  $a_i$  on demand by making  $i$  calls to  $h$ , or store all the  $a_i$  using  $n$  units of memory. Her third option is to implement a *time-storage trade-off*, requiring only about  $\log_2 n$  units of memory and  $\log_2 \sqrt{n}$  calls to  $h$  [6]. Similarly for Bob and the  $b_i$ .

**A1** Wait for a message  $b'$  (supposedly from Bob), then

1. **if**  $h(b') = b_{i+1}$   
**then**  $b_i := b'$ ;  $AcceptKey(b_i)$ ; send  $a_i$ ; set  $i := i - 1$ ; **goto** A0  
**else goto** A1.

**B0** (Bob's initial program state)

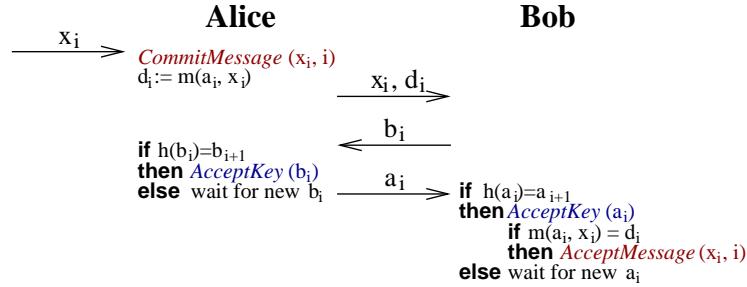
Wait for a message  $(d', x')$  (supposedly from Alice), then

1. send  $b_i$  and **goto** B1.

**B1** Wait for a message  $a'$  (supposedly from Alice), then

1. **if**  $h(a') = a_{i+1}$  **then**
  - (a)  $a_i := a'$ ;  $AcceptKey(a_i)$ ;
  - (b) **if**  $m(a_i, x') = d'$   
**then**  $x_i := x'$ ;  $AcceptMessage(x_i, i)$   
(b) else do not accept any message in epoch  $i$ );
  - (c) set  $i := i - 1$ ; **goto** B0**else goto** B1

Figure 1 gives a simplified view on the protocol.



**Fig. 1.** Simplified description of one epoch of the protocol

*Reliability:* The following reliability properties are met:

**Soundness:** 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.

**Recoverability:** Repeating old messages cannot 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. 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. On the other hand, if Bob receives a faulty  $(x', d') \neq (x_i, d_i)$ , he will refuse to accept *any* message in epoch  $i$ . Recovering means that soundness can be restored in epoch  $i - 1$ .

## 5 Security

### 5.1 Building Blocks and Assumptions

The main cryptographic building block in this paper is a MAC

$$m^* : \{0, 1\}^s \times \{0, 1\}^* \rightarrow \{0, 1\}^s$$

We fix some constant message const and define the two functions  $m$  and  $h$  we actually use in the protocol

$$\begin{aligned} h : \{0, 1\}^s &\rightarrow \{0, 1\}^s, \quad h(k) = m^*(k, \text{const}), \quad \text{and} \\ m : \{0, 1\}^s \times \{0, 1\}^* &\rightarrow \{0, 1\}^c, \quad m(k, x) = \text{truncate-to-}c\text{-bit}(m^*(k, x)). \end{aligned}$$

In the case of  $m$ , a restriction is  $x \neq \text{const}$ . If necessary, we can, e.g., define const as a single zero-bit, and prepend a single one-bit to every message  $x$ .

Security against adaptive chosen message attacks has been established as a standard requirement for MACs:

**Assumption 1** *It is infeasible for the adversary to provide an **existential forgery** in an **adaptive chosen message attack** scenario against  $m^*$ . I.e., the adversary is given access to an authentication oracle, computing  $t_i = m(y, x_i)$  for the adversary, where  $y \in_R \{0, 1\}^s$  is secret and the adversary is allowed to choose arbitrary messages  $x_i$ . “Adaptive” means that the adversary is allowed to choose  $x_i$  after having seen  $t_{i-1}$ . The adversary wins if she can produce a pair  $(x', t')$  with  $m(y, x') = t'$ , without previously asking the oracle for  $m(y, x')$ .*

Unfortunately, this standard assumption is not quite sufficient for our purposes. Below, we will not make use of assumption 1 at all, but instead, define two similar assumptions. Firstly, we use  $m$  instead of  $m^*$  as a MAC, i.e., the truncation of  $m^*$  to  $c \leq s$  bit. The security of  $m$  does not follow from the security of  $m^*$ . So we need to make the same assumption for  $m$  instead of  $m^*$ :

**Assumption 2** *It is infeasible for the adversary to provide an **existential forgery** in an **adaptive chosen message attack** scenario against  $m$ .*

Furthermore, we use  $h$  to build a hash chain, which implies that  $h$  must be one-way. It may be surprising, but  $m^*$  being secure against existential forgery is not sufficient for the one-wayness of  $h = m^*(\cdot, \text{const})$ . If, given  $k^* = h(k) = m^*(k, \text{const})$ , the adversary can find the secret  $k$ , then she can forge messages. But the adversary could just as well find some value  $k' \neq k$  with  $k^* = h(k') = m^*(k', \text{const})$  without necessarily being able to generate existential forgeries. We thus need to exclude this case:

**Assumption 3** *The function  $m^*$  is **one-way**. I.e., given a random  $k \in \{0, 1\}^s$ , and a message const, it is infeasible to find any  $k' \in \{0, 1\}^s$  with  $m^*(k, \text{const}) = m^*(k', \text{const})$ .*

Note that inverting  $m^*$  (i.e., breaking the one-wayness of  $h$ ) would either allow us to find a secret key and thus to forge messages, or provide a 2nd preimage, i.e., a value  $k' \neq k$  with  $h(k) = h(k')$ . Indeed, for our formal proof of security we could replace assumption 3 by assuming 2nd preimage resistance. The proof would be slightly more complicated, though.

## 5.2 Proving Security for Epoch 0

**Theorem 1.** If the adversary can efficiently break epoch 0 of the protocol, she can efficiently break either assumption 2 or assumption 3.

Concrete security. If she can break the protocol in time  $t$  with probability  $p$ , she can either invert  $h$  or forge a message for  $m$  in time  $\leq t + 2t^*$  with probability  $p/2$ . Here,  $t^*$  is the time to evaluate either  $h$  or  $m$ , which ultimately boils down to the time for evaluating  $m^*$ .

*Proof.* Eve can send the following messages (see also left side of Figure 2):

(1) If Alice's program state is A0:  $x_0$  to Alice.

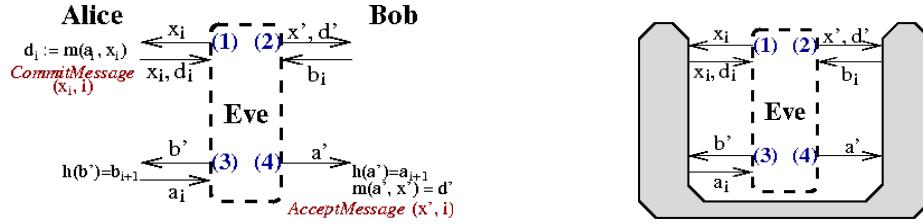
Alice responds  $d_0 := m(a_0, x_0)$  (and  $x_0$ , but  $x_0$  is known to Eve, anyway).

(2) If Bob's program state is B0:  $(x', d')$  to Bob – with  $x' \neq x_0$ .

(3) If Alice's program state is A1:  $b'$  to Alice – with  $h(b') = b_1$ .

(4) If Bob's program state is B1:  $a'$  to Bob – with  $h(a') = a_1$ .

Remember that she is successful if she gets Bob to  $\text{AcceptMessage}(x', i)$  for a message  $x'$  that Alice has not send in epoch  $i$ .



**Fig. 2.** Eve in epoch  $i$

Note that (3)-like messages  $b'$  with  $h(b') \neq b_1$  to Alice do not affect Alice's state; Alice ignores them. Since Eve can check  $h(b') = b_1$  on her own, we assume w.l.o.g. Eve not to send any message  $b'$  with  $h(b') \neq b_1$  to Alice. Similarly, for (4)-like messages, we assume, Eve not to send any  $a'$  with  $h(a') \neq a_1$  to Bob.

In order to successfully attack, Eve *must* send *exactly* one message (1) to Alice (to ensure  $\text{CommitMessage}(x_0, 0)$ ) and both messages (2) and (4) to Bob (for  $\text{AcceptMessage}(x', 0)$ ). Eve may send *at most* one message (3) to Alice. W.l.o.g., we assume Eve to send *exactly* one message (3). (If she wins her attack game without sending message (3), she has sent message (2) and did learn  $b_0$  from Bob. She can always send a final message (3) with  $b' = b_0$ .)

While (1,2,3,4) is the protocol-defined “natural” order for sending the messages, Eve is not bound to this order. There are some restrictions though:

- Message (1) must be sent before message (3). Until she knows and has committed to  $x_0$ , Alice wouldn't even listen to message (3).

- Also, Bob wouldn't listen to (4) before having received (2).

In the context of this proof, we just need to distinguish between two cases, which we represent by two games: Either message (2) is sent before message (3), or the other way. Consider disconnecting Eve from Alice and Bob, and connecting her with either of two games (cf. right side of Figure 2). If we win such a game, we can either invert  $h$  or forge messages. We will show that Eve cannot distinguish her participation in such a game from the “real” attack against the protocol and show that a successful attack by Eve is essentially the same as us winning one of our games. So at the end, if Eve can feasibly attack the protocol, we can feasibly invert  $h(\cdot) = m(\cdot, \text{const})$  or forge messages for  $m^*$ . The games are the following:

1st game (inverting  $h$ ): Given  $k^* = h(k) = m^*(k, 0)$ , for a uniformly distributed random  $k$ , find some  $k'$  with  $m^*(k', 0) = k^*$ .

- Randomly choose  $a_0$ , compute  $a_1 := h(a_0)$ .
- If Eve sends message
  - (1), the value  $x_0$ : compute and respond  $d_0 := m(a_0, x_0)$ .
  - (2): abort the game.
  - (4): Report an error! (Message (2) must be sent before message (4), and this algorithm aborts after message (2).)
- When Eve sends (3), the value  $b'$ : print  $k' := b'$  and stop.

The values provided to Eve during the 1st game are distributed exactly as in the case of the real attack game. Namely,  $a_0$  and  $b_0$  are independent uniformly distributed random values, and all the other values are derived from  $a_0$  and  $b_0$ . Note that if Eve sends message (3) before message (2), the game succeeds; else it doesn't. To compute  $a_1$ , we call  $h$ . To compute  $d_0$ , we call  $m$ . Thus, we need two function calls. As Eve herself runs in time  $t$ , the game takes time  $t + 2t^*$ .

2nd game (existential forgery for  $m$ ): Consider an unknown random  $y$ , known  $y^* = h(y)$ , and the ability to ask an oracle for  $m(y, \cdot)$ . Proceed as follows.

- Set  $a_1 := y^*$ ; randomly choose  $b_0$ ; compute  $b_1 := h(b_0)$ .
- If Eve sends message
  - (1), the value  $x_0$ : ask the oracle for the response  $d_0 = m(y, x_0)$ .
  - (3): abort the game.
  - (4): Report an error!
- When Eve sends (2), the pair  $(x', d')$ : print  $(x', d')$  and stop.

Eve's attack succeeds if and only if  $(x', d')$  is an existential forgery.

Similarly to above, the distribution of values provided during the game is identical to the real attack game. The only computation during the game is the one for  $b_1 := h(b_0)$ , so the game needs time  $t + t^* \leq t + 2t^*$ .

Completing the proof: The 1st game is the counterpart of the second game: one succeeds if message (2) is sent before message (3), the other one, if message (3) is sent before message (2). Eve doesn't know which game we play – or rather, that we are playing games with her at all, instead of mounting the “real” attack. So Eve still succeeds with probability  $p$ . If we randomly choose the game we play, we succeed with  $p/2$ . Neither game takes more than time  $t + 2t^*$ .  $\square$

### 5.3 Security in any Epoch $i$

At a first look, it may seem that the security proof for epoch 0 is also valid for epochs  $i > 0$ . But in epoch 0, the keys for the MAC  $m^*$  are uniformly distributed random values  $a_0$  and  $b_0$  in  $\{0, 1\}^s$ , while later, we use  $a_i$  and  $b_i$ . The problem is as follows.

- Our security assumptions for  $m^*$  require *uniformly distributed* random keys.
- Our security assumptions for  $m^*$  do not ensure the *uniform distribution* of the output values  $a_i = h(a_{i-1}) = m^*(a_{i-1}, 0)$  and  $b_i = \dots$

Now  $m^*$  could be defined such that the one-way function  $h(x) = m^*(x, 0)$  permutes over  $\{0, 1\}^s$ . This would solve our problem, but restrict our choices  $m^*$  too much. In practice, however, most cryptographic MACs can reasonably be assumed to behave *pseudorandomly*. Thus, we make an additional assumption.

Let  $u \in_R \{0, 1\}^s$  be a random variable chosen according to the uniform distribution. Let  $w$  be a random variable chosen by applying the function  $h$  to a uniformly distributed input, i.e.,

$$v \in_R \{0, 1\}^s, \quad \text{and} \quad w := h(v).$$

Let  $A$  be a distinguishing adversary for  $u$  and  $w$ . The advantage  $\text{Adv}_A$  of  $A$  in distinguishing  $u$  from  $w$  is defined in the usual way:

$$\text{Adv}_A = |\Pr[A(u) = 1] - \Pr[A(w) = 1]|$$

**Assumption 4** *No efficient adversary  $A$  can feasibly distinguish the distribution of the random variable  $w = h(v)$ ,  $v \in_R \{0, 1\}^s$ , from the distribution of  $u \in_R \{0, 1\}^s$ . I.e., for all efficient  $A$  the advantage  $\text{Adv}_A$  is negligible.*

Recall that  $h$  is defined by  $h(\cdot) = m^*(\cdot, \text{const})$ . For typical MACs  $m^*$ , this assumption is highly plausible.

We use assumption 4 to prove the pseudorandomness of values  $a_1 := h(a_0), \dots, a_n := h(a_{n-1})$  for a random  $a_0$ , along an entire hash chain.

**Lemma 1.** *If, for any  $i \in \{1, 2, \dots, n-1\}$ , the adversary can efficiently distinguish  $a_i$  from  $a_{i-1}$ , she can also distinguish  $a_1$  from  $a_0$ , thus breaking Assumption 4.*

Concrete security. *Let  $i \in \{1, 2, \dots, n-1\}$  be given. If the adversary can distinguish  $a_i$  from  $a_{i-1}$  in time  $t$  with an advantage  $\alpha$ , she can distinguish  $a_1$  from  $a_0$  in time at most  $t + (i-1) * t^*$  with the same advantage  $\alpha$ . Here,  $t^*$  is the time for evaluating  $h$ .*

*Proof.* Let a value  $r_0$  be given, either distributed like  $a_0$  or like  $a_1$ . Compute  $r_1 := h(r_0), \dots, r_{i-1} := h(r_{i-2})$ . Now,  $r_{i-1}$  is either distributed like  $a_{i-1}$ , or like  $a_i$ , and we can distinguish between both options for  $r_{i-1}$  in the same time and with the same advantage as for  $a_{i-1}$  and  $a_i$ . Computing  $r_{i-1}$  takes at most  $i-1$  calls to  $h$ .  $\square$

One more issue has to be taken into account. In the single-epoch case, we argued that finding 2nd preimages, i.e., values  $a' \neq a_i$  with  $h(a') = h(a_i) = a_{i+1}$  when given  $a_i$ , is infeasible under our assumptions. But when dealing with more than one epoch, Eve might possibly trick Alice into committing to some new message  $x_{i-1}$  and sending  $d_i := m(a_{i-1}, x_{i-1})$  – even before Bob has seen  $a_i$  (see below). In contrast to an ordinary 2nd preimage attack, Eve now does not just know  $a_i$ , but she also has some additional information about  $a_{i-1}$ . Driven by the usual reasonable pessimism, we even assume Eve to know  $a_{i-1}$  itself. We consider finding an  $a' \neq a_i$  with  $h(a') = h(a_i) = a_{i+1}$  as a *guided 2nd preimage*. Theoretically, such guided 2nd preimages might be possible, even under all the assumptions we made so far. Thus, we make one additional assumption.

**Assumption 5** *It is infeasible to find guided 2nd preimages for  $h$ . I.e., given  $a_0 \in_R \{0, 1\}^s$ ,  $a_1 = h(a_0)$ , and  $a_2 = h(a_1)$ , it is infeasible to find any  $a' \neq a_1$  with  $h(a') = a_2$ .*

Recall that the adversary wins in epoch  $i$  if she can make Alice to *CommitMessage*( $x_i, i$ ) and Bob to *AcceptMessage*( $x', i$ ) for any  $x' \neq x_i$ .

**Theorem 2.** *If there is any epoch  $i \in \{0, \dots, n-1\}$  in which the adversary can feasibly win with significant probability, at least one of the assumptions 2, 3, 4, or 5 is false.*

Concrete security. *If she can win in epoch  $i$ , in time  $t$  with probability  $p$ , she can either invert  $h$ , forge a message for  $m$ , or generate a guided 2nd preimage for  $h$  in time  $\leq t + 2t^*$  with probability  $p/4$ . Or she can distinguish  $(a_i, b_i)$  from  $(a_{i-1}, b_{i-1})$  with advantage  $p/4$ . Here,  $t^*$  is the time for calling either  $h$  or  $m$ , which ultimately boils down to calling  $m^*$ .*

*Proof.* For simplicity, we prove the qualitative security claimed in theorem 2, while just sketching how to prove the concrete security claims.

We say, the protocol in a “synchronised state”, if there is an  $i \in \{0, \dots, n\}$  such that Bob knows  $a_i$  but not  $a_{i-1}$ , while Alice knows  $b_i$  but not  $b_{i-1}$ . I.e., the protocol is in a synchronised state if both Alice and Bob are in the same epoch  $i - 1$ . After the initialisation, both are in epoch  $n - 1$ , hence the protocol is in a synchronised state.

The remainder of this proof is organised as follows. We start by analysing to what degree Eve can benefit from a *non-synchronised state*. We then proceed to consider the case of a *synchronised state*. We conclude by sketching how *concrete security* can be added to the proof.

Non-synchronised states: Consider Alice and Bob to be in epoch  $i$ , thus the protocol state is synchronised. Alice will not move forward into epoch  $i - 1$  without having seen  $b_i$  with  $h(b_i) = b_{i+1}$ . If Eve could provide such a  $b_i$  without obtaining it from Bob, she could win in epoch  $i$  anyway. Thus we can safely assume that Alice does not move forward before Bob sends  $b_i$ . For the same reason, we may assume Bob not moving forward to epoch  $i - 1$  without having seen  $a_i$  from Alice. Bob only sends  $b_i$  after having seen  $a_i$  from Alice. Thus, Bob

can never be ahead of Alice. Temporarily, Alice can be ahead of Bob – especially if Eve does not forward  $a_i$  to Bob. This would give a protocol state with Alice living in epoch  $i - 1$  while Bob still lives in epoch  $i$ . But without having seen  $b_{i-1}$ , Alice cannot move ahead into epoch  $i - 2$ , and Bob does not send this while he is still in epoch  $i$ .

At this point, Eve has but two options to proceed. One is to forward  $a_i$  to Bob, thus creating a new synchronised state. The second is to choose a message  $x_{i-1}$  and send it to Alice, who responds with the authentication tag  $d_{i-1} = m(a_{i-2}, x_{i-1})$ . If, after sending  $x_{i-1}$  to Alice, Eve sends the value  $a_i$  to Bob which she has seen before, there is no gain for Eve. The order of messages has changed, but the messages are the same, anyway. To benefit from the second option, Even has to send a value  $a' \neq a_i$  with  $h(a') = h(a_i) = a_{i+1}$  to Bob. If Eve could find such a value  $a'$ , she could find guided 2nd preimages, thus breaking assumption 5.

Synchronised states: Now consider both Alice and Bob being in some epoch  $i$ , and Eve trying to win in this epoch. This part of the proof is done by induction. We start with epoch 0. Recall that if both assumption 2 and assumption 3 hold, the adversary cannot feasibly win in epoch 0.

Now assume that no efficient adversary can win in epoch epoch (i-1), but there is an efficient algorithm to win epoch  $i$  with significant probability. Clearly, we can use this algorithm to distinguish  $(a_{i-1}, b_{i-1})$  from  $(a_{i-2}, b_{i-1})$ , thus breaking assumption 4.

Concrete security (sketch): This part is quite similar to the proof of theorem 1, the single-epoch case. Instead of two different games, we need to define four:

1. One game to invert  $h$  (like the 1st game in the proof of theorem 1).
2. One game to forge messages for  $m$  (like the 2nd game above).
3. One game to generate guided 2nd preimages for  $h$ .
4. One game to distinguish  $(a_{i-1}, b_{i-1})$  from  $(a_{i-2}, b_{i-1})$ .

If Eve wins, we succeed in at least one of the games. Which game we succeed in depends on Eve's behaviour. As we must commit to one game in advance (i.e. before we know how Eve behaves), the probability of success decreases from  $p$  (for Eve) to  $p/4$  (for us).  $\square$

## 6 Final Remarks and Conclusion

*Attacks Circumventing the Protocol Logic:* In practice, many protocols are broken by attacks which circumvent the protocol logic.

A *replay* attack means that the adversary repeats authentic messages sent before, in a different context. Consider message  $x_i$ , which Alice has committed to in epoch  $i$ . A successful replay attack is tantamount to making Bob accept  $x_i$  in a later epoch  $j$ , while Alice did not commit to  $x_i$  in epoch  $j$ . By our security analysis, we have proven that this is infeasible (if our assumptions hold, that is).

Cryptographic protocols often can be attacked if *several protocol sessions run in parallel*. E.g., an authentic message from one protocol run is put into a different context by repeating it in another session. In our case, however, note that we required the keys  $a_0$  and  $b_0$  to be chosen independently from the keys of other sessions. If messages from other protocol runs could help the adversary, the adversary could as well simulate the other protocol runs for herself, and thus attack even a single protocol run, without any parallel sessions. From our security analysis, we know this isn't feasible.

The Jane Doe protocol does not provide security against *denial of service attacks*. I.e., if Eve sends a fake  $d_i$  in epoch  $i$ , Bob will send  $b_i$  and then not accept the “real”  $d_i$  Alice may later send.

*Freshness* means that a message has been committed to recently. In our case, when Bob accepts message  $x_i$  in epoch  $i$ , he can be sure that Alice (following the protocol rules) did not commit to that message before she had seen and verified Bob's response  $b_{i+1}$  from the previous epoch. In this sense, our protocol ensures the freshness of the messages authenticated.

The messages are “fresh” by belonging to the current epoch. But Eve is able to stretch any epoch at her will. Assume, e.g., that Alice commits to a message  $m_i = \text{“I am well”}$ , but Eve delays forwarding  $d_i = m(a_i, \text{“all is well”})$  to Bob. Later, Alice would need to raise an alarm, but instead Eve forwards  $d_i$  to Bob who sends  $b_i$ , which Eve immediately forwards to Alice. The protocol logic would require Alice to reply  $a_i$ , thus confirming that she is well. Instead of confirming such an outdated message, Alice could simply terminate communication with Bob. Eve has the power to cut the communication between Alice and Bob, anyway, and Bob will eventually notice that Alice doesn't respond any more.

*Our Assumptions:* One might note that our assumptions are nonstandard. Our first objective was to improve the existing flawed protocol from [21] in such a way that it preserves efficiency and suitability for low-end devices while closing the security weakness. We claim that our assumptions are very plausible for any decent message authentication code, such as the AES-based CMAC [16] and any instance of the HMAC<sup>5</sup> [17] when based on a secure hash function. In a theoretical setting, it is easy to see that instantiating  $m^*$  by HMAC based on an underlying random oracle would satisfy our requirements.

In fact, assuming

some underlying primitive (from which we derive  $m^*$ ) to behave like a random oracle is theoretically sound and would allow us to greatly simplify our security proofs. But in practice, cryptographic primitives never behave like random oracles. Results in the random oracle model hardly provide any guideline for the choice of a good primitive. Our very specific standard model assumptions on  $m^*$  are meant to serve as such a guideline.

Note that we have two functions, a message authentication code (MAC)  $m$  and a hash function  $h$ , both of which are derived from another MAC  $m^*$ . In

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<sup>5</sup> The basic structure of HMAC is as follows. Given two constants  $\text{ipad} \neq \text{opad}$  and a hash function  $H$ ,  $\text{HMAC}(K, x)$  is defined as  $H(K \oplus \text{opad}, H(K \oplus \text{ipad}, x))$ .

principle, one could choose  $m$  and  $h$  independently from each other, without deriving them from the same underlying primitive, as has been suggested in [13]. Under appropriate assumptions, one can still prove the security of the Jane Doe protocol. This requires more complex and less natural assumptions than those made here. Even if  $m$  is a secure MAC and  $h$  is modelled as a random oracle, the protocol may actually be insecure. We give a pathological example in Appendix C. Deriving both  $m$  and  $h$  from one single primitive  $m^*$  thus saves us from some difficult technical issues.

Furthermore, we believe that deriving both  $h$  and  $m$  from the same underlying primitive is natural and meets practical necessities very well.

*Conclusions:* Entity recognition is an adopted security goal especially useful for constrained pervasive applications. An attack following the Dolev-Yao adversary model against an entity recognition protocol published at SAC 2003 [21] was presented. The Jane Doe protocol provides entity recognition. The protocol is efficient, runs on very low-end devices, and is provably secure. We believe this to be a significant step into the direction of provably secure protocols for low-end devices.

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## Appendix

### A Bi-Directional Schemes

Note that in the Jane Doe protocol, the role of the sender is always assigned to Alice, while Bob is always on the receiving end. In practical applications, it may be desirable to have both Alice and Bob change roles at will. In this case, each of them should have two hash chains: One that is used for committing to sent messages and one for acknowledging received ones.

Of course, it is tempting to build a bi-directional scheme, using just one hash chain per party. This way, memory and/or computing power could be saved for both Alice and Bob. However, if both Alice and Bob can initiate a message, the following middleperson attack becomes possible:

- (1) Eve sends random values  $(x_i, d_i)$  to Alice, who responds with  $a_i$ .
- (2) For the fake message  $\hat{x}_i$ , Eve computes  $\hat{d}_i := m(a_i, \hat{x}_i)$  and sends  $\hat{x}_i, \hat{d}_i$  to Bob.

- (3) Bob replies with  $b_i$ .
- (4) Eve sends  $a_i$  to Bob, who conducts both tests (hash chain and message authentication) and concludes that the message is indeed from Alice.

Obviously, the same attack can be used to impersonate Bob. Also note that Eve knows an unused value  $b_i$ , but since she has already sent random values  $(x_i, d_i)$  to Alice, she can not use it to fake a message from Bob.

Things get even worse if we build a bi-directional scheme on only one hash chain using less protocol steps. One idea could be to have Bob reply immediately on every message originated by Alice, and vice versa. This way, a communication round can be initiated by either Alice or Bob and consists of one message per party. In the original protocol, the protocol steps would be as follows:

1. Alice sends  $(x_i, d_i)$ .
2. Bob replies  $b_i$ .
3. Alice verifies  $b_i$  and sends  $a_i$ .
4. Bob verifies  $a_i$  and  $d_i$  and sends  $(x_{i+1}, d_{i+1})$ .
5. Alice replies  $a_{i+1}$ .
6. Bob verifies  $a_{i+1}$  and sends  $b_{i+1}$ .
7. Alice verifies  $b_{i+1}$  and  $d_{i+1}$ .

Note that Alice sends  $a_i$  (in step 3) and  $a_{i+1}$  (in step 5) without any verification in between. Thus, we might want to save on protocol steps by leaving out step 5. But then the following attack becomes possible:

- (1) Eve sends random values  $(x_i, d_i)$  to Alice, who responds with  $a_i$ .
- (2) (step 1) For the fake message  $\hat{x}_i$ , Eve computes  $\hat{d}_i := m(a_i, \hat{x}_i)$  and sends  $\hat{x}_i, \hat{d}_i$  to Bob.
- (3) (step 2) Bob replies  $b_i$ .
- (4) (step 3) Eve sends  $a_i$ .
- (5) (step 4) Bob verifies  $a_i$  and  $\hat{d}_i$  and sends  $(x'_{i+1}, d'_{i+1})$ .
- (6) (step 6) Bob also sends  $b_{i+1}$ .

At this point, an epoch is concluded for Bob, and he has accepted Eve's faked message. At the same time, Alice is waiting for  $b_i$ . Now Eve proceeds as follows:

- (7) Eve sends  $b_i$  to Alice.
  - (8) Alice checks  $d_i$  and sees that the value is wrong. She asks for re-transmission.
  - (9) Eve chooses a message  $\hat{x}_{i+1}$ , computes  $\hat{d}_{i+1}$  and sends  $(\hat{x}_{i+1}, \hat{d}_{i+1})$  to Alice.
  - (10) Alice checks for correctness, but does not accept the message as authentic.
- Depending on the protocol definition, she either replies (delivering another  $a_{i+1}$  to Eve) or starts a new protocol round.

Note that at this point, Eve has an unused value  $b_{i+1}$  from Bob and possibly even an unused value  $a_{i+1}$  from Alice. Thus, she can send one or two faked messages with even less effort.

Concluding, a bi-directional scheme where both Alice and Bob can initiate a message must use two hash chains. Things look different if Alice and Bob

communicate in duplex mode, meaning that messages originate with Alice and Bob in a strictly alternating fashion. In this case, Alice and Bob go through the states A1-A2-B1-B2, in strictly that order. The proof of security can be adapted to suit this expansion of the protocol.

## B Public-Key Techniques: A Crude Comparison

Public-key techniques are not always an option. Below, however, we assume that it is possible to use public-key techniques. Solving the entity recognition problem by the means of **digital signatures** is straightforward: In the initialisation phase, Alice sends her public verification key to Bob. Later, Alice signs each message, and Bob verifies all the signatures. Even if our devices are able to compute digital signatures (or to verify them) at all, doing so for every single message can be too expensive. One could, however, employ the Diffie-Hellman key exchange during the initialisation phase, to create a secret authentication key  $k$  shared by Alice and Bob. Later, Alice authenticates each message  $x_i$  by a MAC  $d_i := m(k, x_i)$ . (If we care about the freshness of messages, we would have to extend  $x_i$  by some additional nonce value chosen by Bob, while our proposed protocol provides *freshness for free*.)

Note that our protocol limits the number of messages to be authenticated in advance, while the signature-based and the key-exchange-based approach can be used indefinitely. Here, however, we focus on *power consumption*. For wireless sensor networks, power consumption is a major issue. So which approach consumes less power: the Jane Doe protocol or a method using Diffie-Hellman key exchange? The power consumption for receiving messages and for computing the MAC is considered negligible, compared to the expensive operations of sending messages and doing the Diffie-Hellman key exchange.

To exemplify this issue with some numbers, we estimate that the public-key operation (one Elliptic-Curve point multiplication) needs (at least) 300 mJoules (cf. [11]). Similarly, we estimate that the transmission of one bit over a distance of 5 ft  $\approx$  1.6 m requires  $1 \mu\text{J}$  [5]. For larger distances, we generalise this: Transmitting  $x$  bit over  $y$  m requires  $xy^2/2.56 \mu\text{J}$ . We assume that Bob's messages  $b_i$  are of the size  $s = 80$  bit, and there are  $n$  such messages. So our protocol is better if

$$\frac{80y^2n}{2.56} < 300\,000,$$

i.e. if the distance  $y$  between Alice and Bob is less than 31 m for  $n = 10$  or less than 9.8 m for  $n=100$ .

This is a very sketchy comparison of the costs for Bob to compute an authentication key in a Diffie-Hellman setting to the cost for Bob sending links of his hash chain during the Jane Doe protocol. We ignored Alice's point of view, the size of packet headers, the influence of noise and corrupted messages, the cost for maintaining the hash chain (cf. Footnote 4), the cost for sending messages during the initial Diffie-Hellman key exchange, ... and we made assumptions on

the power consumption. Our point was to give a brief outline, how one *can* compare protocols, given the correct power consumption numbers of a real system. A more thorough comparison can be based, e.g., on the methodology in [22].

Also recall that in many application scenarios, the usage of public-key techniques may be prohibitive, and power consumption is not always the main bottleneck. E.g., RFID-tags are typically required to respond quickly, given some inductive power supply for a short amount of time.

## C Deriving both $h$ and $m$ from $m^*$

**Why do we derive both  $h$  and  $m$  from the same underlying primitive  $m^*$ ? A Pathological Example.** The one-wayness of  $h$  and the security of  $m$  are *not quite sufficient* for the protocol’s security, even in the single-epoch case. Recall that a secret  $a_0$  is used as a MAC-key,  $d_1 = m(a_0, x_1)$  is authentication tag for the message  $x_1$ , and  $a_1 = h(a_0)$  is a link in the hash chain, known to the adversary. So  $h$  and  $m$  interact by using the same “key”  $a_0$ . In an unpublished version of this paper, we made an *additional* assumption of  $h$  and  $m$  being “combinedly secure”. This introduced a rather unusual kind of assumption, and complicated the proofs a lot, compared to our current approach.

To illustrate why some kind of “combined security” is required, consider the following pathological example:

- Model  $h$  as a random oracle.
- Define a MAC  $m(y, x) = (m'(y, x), h(y) \oplus y)$ , where  $m'$  is another MAC.

Clearly, a random oracle  $h$  is one-way. And, with  $h$  being a random oracle, breaking Assumption 1 implies breaking the same assumption for  $m'$ . Thus, if  $m'$  is secure, then so is  $m$ .

But in the case of the Jane Doe protocol, Eve does learn  $a_1 = h(a_0)$ . Given the authentication tag  $d_1 = m(a_0, x_1) = (m'(a_0, x_1), h(a_0) \oplus a_0)$  for any message  $x_1$ , she can easily compute the secret  $a_0$  and then forge authentication tags at will. This allows her to replace  $d_1$  by  $d' = m(a_0, x')$  for an arbitrary  $x' \neq x_1$ , and then present  $a_0$  to Bob, who will accept  $x'$ .

In spite of using individually secure  $h$  and  $m$ , the protocol is completely broken, since the combined usage of  $h$  and  $m$  under the same “key”  $a_0$  is insecure.