

# An Authentication Protocol For Mobile Agents Using Bilinear Pairings

Amitabh Saxena, and Ben Soh  
Dept. of Computer Science and Computer Engineering  
La Trobe University, Bundoora, VIC, Australia 3086

August 24, 2005

## Abstract

A mobile agent is a mobile program capable of maintaining its execution states as it migrates between different execution platforms. A key security problem in the mobile agent paradigm is that of trust: How to ensure that the past itinerary (of execution platforms) claimed by the agent is correct. This is necessary in order to establish a reasonable level of trust for the agent before granting execution privileges.

In this paper we describe a protocol using bilinear pairings that enables trust relationships to be formed between agent platforms in an ad-hoc manner without actively involving any trusted third party. This protocol can be used to authenticate agents before granting execution privileges. The main idea behind our approach is the concept of ‘one-way’ chaining.

## 1 Introduction

Mobile agents are agents that can physically travel across networks and perform tasks on machines that provide agent hosting capability. This allows processes to migrate from computer to computer, for processes to split into multiple instances that execute on different machines, and to return to their point of origin. A detailed discussion of mobile agents is beyond the scope of this paper and the reader is referred to [1]. Two foremost security challenges for mobile agents are (a) host protection and (b) agent protection. Our work on mobile agents is only focused only on host protection. For work on agent protection the reader is referred to [2, 3, 4, 5].

In contrast to approaches for host protection based on sandbox environments or other forms of code validation, our model aims to validate the itinerary of an agent. Our approach to security is based on a notion of trust which is summarized as follows: If all entities involved with the agent can be authenticated, a level of trust can be established, which can then be used for granting or denying execution privileges. Current solutions for host protection rely on tamper

proof hardware, an on line trusted third party or a ‘sandbox’ model of execution [6, 7, 8]. Our method does not require any such measures. We use the concept of *one-way* signatures to connect arbitrary hosts in a chain of trust, thus enabling ad-hoc trust relationships to be formed.

The concept of one-way signature chaining was proposed in [9] and [10] where the authors constructed authentication protocols for mobile agents using hypothetical cryptographic primitives known as *strong non-commutative associative one-way functions*. The authors also asked if an equivalent protocol can be constructed using any existing cryptographic primitives. In this paper, we answer this question affirmatively and show that the mobile agent authentication protocol presented in [10] can be constructed using bilinear pairings, thus settling their open question.

Although the original concept of signature chaining presented in [10] is based on a standard certificate based Public Key Infrastructure (PKI), it can be shown that their model can be reduced directly to an Identity-Based Public Key Cryptosystem (ID-PKC) or a Certificate-Less Public Key Cryptosystem (CL-PKC) due to certain properties of the one-way function used.<sup>1</sup> In contrast to this, the protocol presented in this paper is based on a standard certificate based PKI and it is not known if a direct reduction to an ID-PKC or a CL-PKC exists.

## 2 Background

Any entity that runs a mobile agent platform server is called a *host*. We assume that all such hosts are identified by a public directory. Any host that initiated an agent into the system is called the *initiator* of the agent. Agents can migrate autonomously between different host platforms. This act of migration is called *agent transfer*. An *instance* of an agent is a snapshot of its state at any point of execution on some platform. An *itinerary* is the ordered list of hosts visited by an agent.

### 2.1 Agent partitioning

Using the object oriented paradigm, we assume that any instance of a mobile agent can be split (or partitioned) into a *static* part (consisting of object methods) which is unchanging as the agent hops across platforms and a *dynamic* part (consisting of data and the state information of the interacting objects) that changes at each hop. Depending on the specific implementation, the partitioning schemes can differ. However, in this section we enumerate certain properties relevant in our context.

1. *Unique*: It may be possible that an instance of the agent can be partitioned in more than one ways. A partition scheme is *unique* if all instances of the agent have a unique static and dynamic part.

---

<sup>1</sup>The reader is referred to [11] for a discussion of an ID-PKC and to [12] for a discussion of a CL-PKC

2. *Identical*: A partition scheme is *identical* if all instances of the agent have at least one common static part.
3. *Mutually authenticating*: We further assume that some static and dynamic parts can be made mutually inseparable. This means that the agent’s functionality is available if and only if both the static and dynamic parts correspond to the same agent. Mixing and matching between different agents is not possible. We say that the scheme is *mutually authenticating* if all instances of the agent have at least one mutually inseparable partition.
4. *Ideal*: A partitioning scheme is *ideal* if it is unique, identical and mutually authenticating.

## 2.2 Authentication Requirements

In this section, we give the high-level authentication requirements for our model. we define the following two requirements:

1. *Initiator authentication*: Is the claimed initiator the same as the real initiator?
2. *Itinerary authentication*: Is the claimed itinerary the same as the real itinerary?

Our requirement for unconditional security is itinerary authentication. It is evident, however, that this will also always involve initiator authentication, since the initiator is the first host in the itinerary. We introduce the concept of *relative authentication* to imply that the first host (the initiator) in an itinerary is unknown. On the other hand, *absolute authentication* implies that the initiator can be authenticated.

## 2.3 One-way Chaining

Represent the host platforms as points of an acyclic directed graph. As the agent hops, a new arc directed from the receiver to the sender is added to the graph. The edges of such a graph will represent a hop-by-hop path of the agent in the reverse direction from the current host to the initiator. In this notation the statements “*a* passed the agent to *b*” and “There is a path of unit length from *b* to *a*” are considered equivalent. We can consider this graph to describe the path by which trust is propagated in the system.<sup>2</sup>

1. We say that a *direct* path exists from *b* to *a* if and only if *b* can prove (in the context of the agent) something about *a* that no other host can. That is, *b* has some *extra* information about *a* that others cannot extract from *b*’s proof.

---

<sup>2</sup>We intuitively define trust to propagate in the reverse direction of the agent. If the agent moves from *a* to *b*, we are interested to know if *b* trusts *a*. That is, if there is path from *b* to *a*. Moreover we are only interested in those hosts that modified the dynamic part.

2. Let  $\{h_0, h_1, \dots, h_n\}$  be a set of hosts for some  $n \geq 1$ . We say a *chained* path exists from  $h_n$  to  $h_0$  if and only if there exists a direct path from  $h_x$  to  $h_{x-1}$  for each  $x$  from 1 to  $n$ .
3. We say that there is a *one-way* chained path from  $b$  to  $a$  if and only if there is a chained path from  $b$  to  $a$  and there is no (direct or chained) path from  $a$  to any other host.

Assume that  $i$  is the initiator of the agent,  $a$  is any sending host and  $b$  is the receiving host. Also, excepting the act of agent transfer no other interaction is allowed between any hosts. Using this scenario, authentication can be redefined in the context of  $b$  as follows:

- (a) *Relative*: Determine that a chained path from  $a$  to  $i$  exists.
- (b) *Absolute*: Determine that a one-way chained path from  $a$  to  $i$  exists.

## 2.4 Fixed Strings

Let  $L_1$  and  $L_2$  be any two languages. For some  $x \in L_1$  and some  $y \in L_2$ , the ordered pair  $(x, y)$  is said to be *fixed* if and only if there exists a (polynomial-time computable) binary function  $\sigma : L_1 \times L_2 \mapsto \{0, 1\}$  such that  $\sigma(x, y) = 1$  and it is computationally intractable to find another string  $\hat{y} \in L_2$  such that  $\sigma(x, \hat{y}) = 1$ .

## 2.5 Bilinear Pairings

The fundamental building blocks of our protocol are a class of primitives known as *bilinear pairings*.<sup>3</sup>

Let  $\mathbb{G}_1$  be a cyclic additive group generated by  $P$ , whose order is a prime  $q$  and  $\mathbb{G}_2$  be a cyclic multiplicative group of the same order. Assume that computing the discrete logarithm in both  $\mathbb{G}_1$  and  $\mathbb{G}_2$  is hard. A bilinear pairing is a map  $e : \mathbb{G}_1 \times \mathbb{G}_1 \mapsto \mathbb{G}_2$  and satisfies the following properties:

1. *Bilinearity*:  $e(aP, bQ) = e(P, Q)^{ab}$  For all  $P, Q \in \mathbb{G}_1$  and  $a, b \in \mathbb{Z}_q$ .
2. *Non-degeneracy*:  $P \neq 0 \Rightarrow e(P, P) \neq 1$ .
3. *Computability*:  $e$  is efficiently computable.

---

<sup>3</sup>Bilinear pairings are probably best known for their use in Identity Based Encryption (IBE) by Boneh and Franklin in 2001 [11]. Many other applications of bilinear pairings are known. For example, various types of Identity Based Signatures (IBS) [13, 14, 15, 16, 17, 18, 19], tripartite one-round key agreement [20], Certificate-Less Public Key Cryptography (CL-PKC) [12], threshold signcryption [21], self-blindable credential certificates [22] and authenticated key agreement [23] are all based on pairings. Over the past few years, bilinear pairings have become probably the most researched area of cryptography.

Typically, the map  $e$  will be derived from either the Weil or Tate pairing on an elliptic curve over a finite field. Despite the fairly complex mathematics involved in constructing such maps, cryptographic protocols based on pairings can be described entirely without ever referring to the actual implementation. Pairings and other parameters should be selected in proactive for efficiency and security. We refer the reader to [24, 11, 25] for details on generating secure parameters for such pairings.

### 3 Problem Formulation

In this section, we will define the problem of host protection using authentication primitives and set out the goals of our proposed authentication protocol. Although we consider only one agent in our analysis, this setup can also be used in a multi-agent system. We model our protocol on the following assumptions:

1. The mobile agent can be partitioned using an ideal scheme (see section 2.2). Represent by  $M$ , the static part and by  $D_i$  the dynamic part of the  $i_{th}$  instance. For any agent  $\{M, D_i\}$ , the sending, platform is  $I_i$  and the receiving platform is  $I_{i+1}$ . The initiator of the agent is  $I_0$
2. To enable absolute authentication, we require that the pair  $(M, I_0)$  be fixed (see section 2.4). A possible approach for this is to involve a Trusted Third Party (TTP) to certify this pair. The TTP ensures that the same pair cannot be reused again for a certain period of time. We note, however, that it may also be possible to implicitly fix the pair  $(M, I_0)$  (without involving a TTP) using the methods for code obfuscation, undetachable signatures and watermarking described in [2, 4, 5, 26, 27, 28, 29, 9]. For simplicity, in this paper, we assume a TTP is used to fix the pair  $(M, I_0)$ .<sup>4</sup>
3. There is no limit to the number of times an agent may be transferred. The only restriction is that an agent must not return back to a past platform. The exception to this is when the agent returns back to the originator at the end of its itinerary.
4. The itinerary of the agent is ‘ad-hoc’. It is not possible for any platform  $I_i$  to determine the exact future itinerary of the agent (we can consider the agent to be autonomous in this case). Due to this assumption, a sending platform may not know the real identity of the next receiving platform. For simplicity, we assume that any sending platform  $I_i$  *does not* know the identity of the next receiving platform  $I_{i+1}$  and thus, any receiver of the

---

<sup>4</sup>The concept of *liability* is worth mentioning here. In most cases, trust and liability go hand in hand: If Alice is trusted, she is liable if she fails the trust. An attacker will try to gain more trust but not liability. In the situation mentioned here, if the attacker removes all the names from the list and  $(M, I_0)$  is not fixed, it may be possible that the attacker becomes automatically more liable (since the attacker’s name cannot be removed from the list). We can safely ignore this possibility in applications where the liability of removing the names outweighs the the benefit gained from such an attack.

agent is anonymous. This is a useful and necessary assumption considering the vast implications of mobile agents in e-commerce.

5. Agent transfer is done over an insecure public channel. This is in light of the above assumption that any receiver of the agent is anonymous.<sup>5</sup>
6. The mobile agent *must* always transferred with an accompanying signature. Each receiving platform  $I_i$  *must* verify the signature of the previous platform before it is executed. Execution should only be possible if the verification process succeeds and other security policies of the platform are satisfied.
7. Each sending platform  $I_i$  *must* sign the agent after it completes execution and before it is transferred. Moreover if this sending platform is not the first platform in the chain, it should sign the agent only if the verification process on the signature of the previous platform succeeded.
8. Each receiving platform would like to know the exact order of the platforms involved in passing (and executing) the agent. The purpose of the signature scheme is to ensure that the verification process succeeds if and only if the correct order of participants is given as input to the process. Any misbehavior (deviation from the signing or verification process) should be detected along with the concerned participant(s).
9. A Public Key Infrastructure (PKI) will be used for creating and verifying signatures (in the next section, we will describe this PKI). If needed, the same or a different PKI can be used for encryption.

## 4 Our Authentication Protocol

A one-time initial setup is necessary during which our participants create a public-key directory. Once this setup is complete, Any member can initiate an agent into the system. Members can also execute an agent and transfer agents to other members. Our protocol allows multi-hop agents to be authenticated. First we give some more notation: If  $A$  is a non-empty set, then  $x \leftarrow A$  denotes that  $x$  has been uniformly chosen in  $A$ . If  $x$  and  $y$  are two strings then the symbol  $x||y$  denotes the concatenation of  $x$  and  $y$ .

### 4.1 Initial Setup (Create PKI)

In this section we describe how to setup a public directory (or PKI) that will be used to authenticate messages (and if necessary to encrypt them). The PKI we

---

<sup>5</sup>A weak type of secure channel can be obtained by using a ‘proxy’ identity that cannot be linked to the real identity. Revealing this proxy identity cannot compromise the real identity of the receiver. To obtain a weak secure channel, we can consider that the agent is encrypted using an uncertified public key before transfer. This unauthenticated public key can be specified either by the anonymous receiver or by the agent itself.

describe is based on bilinear pairings.<sup>6</sup> A trusted central authority is responsible for creating the PKI. To participate in the authentication protocol, each user must have a certified public key (We consider the process of certification outside the scope of our protocol). The setup protocol proceeds as follows:

1. Let  $e$  be a bilinear map as defined in section 2.5. Define a (one-way) cryptographic hash functions  $H : \{0, 1\}^* \mapsto \mathbb{G}_1$ . Let  $P$  be a generator of  $\mathbb{G}_1$ . The parameters  $\langle e, \mathbb{G}_1, H, q, P \rangle$  are generated by the trusted authority and made public in an authentic way.
2. Each participant  $I_i$  generates  $x_i \leftarrow \mathbb{Z}_q$  as the private key. The corresponding public key is  $Y_i = x_i P$
3. Each participant who wants to sign messages obtains a certificate from some trusted CA linking the identity  $I_i$  and the public key  $Y_i$

This infrastructure can also be used to encrypt messages to any receiver  $I_j$  using the (certified or uncertified) public key  $x_j P$  as follows: The sender will first encrypt the message with a symmetric cipher (such as IDEA) using the key derived from  $K_j = r_j(x_j P)$  where  $r_j \leftarrow \mathbb{Z}_q$ . The sender will transmit the ciphertext along with the partial key  $L_j = r_j P$  using an insecure public channel. Receiver  $I_j$  can compute the same key-derivation key  $K_j = x_j L_j$  to decrypt the ciphertext. Observe that this protocol is secure if the Diffie-Hellman Problem (DHP) is hard in  $\mathbb{G}_1$ . Authentication of the sender will be done using the protocol described next.

## 4.2 Agent Initiation

As mentioned earlier, the initiator  $I_0$  will use a TTP to fix the pair  $\{M, I_0\}$  to ensure that a different user cannot act as the initiator for the same agent later on. It asks the TTP to certify the ordered pair  $(M, I_0)$  using a standard signature scheme (like RSA). Denote by  $C$ , the certificate from the TTP. To avoid chosen ciphertext attacks, a time stamp is included in the certificate. Users who created their public keys after this time are precluded from participating in this protocol.

## 4.3 Transfer Protocol

An arbitrary participant  $I_i$  will process the agent as follows: On receiving it from  $I_{i-1}$ , it first follows the verification procedure and aborts if it fails. Before passing the agent (after execution) to  $I_{i+1}$ , it follows the signing procedure.<sup>7</sup>  $I_0$ , however, only follows the signing procedure. The ordered list of participants,

---

<sup>6</sup>Although bilinear pairings are mostly known for their use in identity based cryptography, other non-identity based applications also have been proposed [24, 30, 31]. Our authentication protocol presented here is based on an ordinary certificate based PKI.

<sup>7</sup>We observe that it is possible to combine the signing and verifying procedures into a single *sign-verify* procedure. However, there will always be a temporal ordering with verification and signing in our case (corresponding to before and after execution of the mobile agent)

“ $I_0, I_1, \dots, I_i$ ” and the certificate  $C$  are part of the signature. As mentioned earlier, we assume that messages and signatures are sent over a secure encrypted channel. Thus if both the sender  $I_i$  and the receiver  $I_{i+1}$  are honest, an eavesdropper does not have access to the signature of  $I_i$  sent to  $I_{i+1}$ .

Essentially our scheme is an *ordered* group signature scheme (i.e. one where the order of the individual signers needs to be preserved). Our approach is to first construct a an ‘un-ordered’ scheme and then use *link verifiers* to ascertain the order of any link in the chain. A link verifier is simply a string identifying the ordered (sender-receiver-message) pair and signed by either the sender or the receiver. We thus have two types of link verifiers: *forward* link verifiers which are signed by the sender and *backward* link verifiers which are signed by the receiver. For instance, the backward link verifier for the message  $M$  passing from Alice to Bob is simply the Bob’s signature on the ordered pair  $\{“Alice, Bob”, M\}$ .

To ensure that the order of the hosts is preserved, we will require all senders to include their backward link verifiers for the message being passed.<sup>8</sup> We propose two different variants of our scheme with identical functionality to illustrate how we convert an ordinary unordered scheme to an ordered one.

## Notation

In the definitions below we assume that MESSAGE denotes the agent which consists of both static and dynamic parts.

1. A correctly formed signature consists of a certificate CERTIFICATE, a list of identifiers IDENTIFIER-LIST, a signature on the static part STATIC-PART, a signature on the dynamic part DYNAMIC-PART and a list of backward link verifiers BACKWARD-LINK-VERIFIER-LIST
2. The signing procedure CREATE-CHAIN-SIGNATURE takes three inputs: a valid message MESSAGE, a valid signature OLD-SIGNATURE and an identifier IDENTIFIER. It outputs a new signature NEW-SIGNATURE or ERROR. We assume that the current user’s private key is implicitly given as input to the signing function.
3. The verification procedure, VERIFY-CHAIN-SIGNATURE takes two inputs: a message MESSAGE and a signature SIGNATURE and outputs TRUE or FALSE.
4. Since  $I_0$  is the first participant, it invokes the signing function with an empty IDENTIFIER-LIST and an empty BACKWARD-LINK-VERIFIER-LIST while  $I_1$ , the second participant invokes the signing function with an empty BACKWARD-LINK-VERIFIER-LIST.
5. Let  $U_0 = x_0H(M)$  and  $U_i = x_iH(M) + U_{i-1}$  for  $i > 0$ . Also let  $V_0 = Y_0$  and  $V_i = Y_i + V_{i-1}$  for  $i > 0$

---

<sup>8</sup>The use of forward link verifiers is not possible since we assumed that any receiver of the agent is anonymous (see section 3).



$$\text{Thus } U_i = \sum_{r=0}^{r=i} x_r H(M) \text{ and } V_i = \sum_{r=0}^{r=i} Y_r = \sum_{r=0}^{r=i} x_r P$$

#### 4.3.1 Variant 1

In this scheme,  $I_i$  will also use the same private key  $x_i$  to sign the dynamic part  $D_i$  and the link verifiers. We additionally define:

$$W_i = x_i H("I_{i-1}, I_i" \| M) \text{ for } i > 0 \text{ and}$$

$$Z_i = x_i H(D_i \| M)$$

##### (A) CREATE-CHAIN-SIGNATURE

This procedure takes as input the MESSAGE  $\{M, D_i\}$ , the IDENTIFIER  $I_i$ , the signature OLD-SIGNATURE and outputs NEW-SIGNATURE or ERROR where

$$\text{OLD-SIGNATURE} = \{C, "I_0, I_1, \dots, I_{i-1}", U_{i-1}, \{W_1, W_2, \dots, W_{i-1}\}, Z_{i-1}\} \text{ and}$$

$$\text{NEW-SIGNATURE} = \{C, "I_0, I_1, \dots, I_i", U_i, \{W_1, W_2, \dots, W_i\}, Z_i\}$$

We describe this procedure algorithmically:

1. Output ERROR if OLD-SIGNATURE, MESSAGE or IDENTIFIER has an invalid structure.
2. Extract  $I_i$  from IDENTIFIER and extract  $\{M, D_i\}$  from MESSAGE. Output ERROR if the private key  $x_i$  corresponding to  $I_i$  is not known.
3. Extract  $C$  from CERTIFICATE of OLD-SIGNATURE
4. Extract " $I_0, I_1, \dots, I_{i-1}$ " from IDENTIFIER-LIST of OLD-SIGNATURE
5. Extract  $U_{i-1}$  from STATIC-PART of OLD-SIGNATURE
6. Extract the ordered list of backward link verifiers  $\{W_1, W_2, \dots, W_{i-1}\}$  from BACKWARD-LINK-VERIFIER-LIST of OLD-SIGNATURE
7. Create IDENTIFIER-LIST = " $I_0, I_1, I_2, \dots, I_i$ "
8. Create STATIC-PART,  $U_i = x_i H(M) + U_{i-1}$
9. Create DYNAMIC-PART,  $Z_i = x_i H(D_i \| M)$
10. If  $(i > 0)$ , create the new backward link verifier  $W_i = x_i H("I_{i-1}, I_i" \| M)$
11. If  $(i > 0)$ , Create BACKWARD-LINK-VERIFIER-LIST =  $\{W_1, W_2, \dots, W_i\}$
12. Output NEW-SIGNATURE = {CERTIFICATE, IDENTIFIER-LIST, STATIC-PART, DYNAMIC-PART, BACKWARD-LINK-VERIFIER-LIST}

### (B) VERIFY-CHAIN-SIGNATURE

For clarity, we describe the verification procedure to be followed by  $I_{i+1}$ . This procedure takes as input the MESSAGE  $\{M, D_i\}$ , the signature SIGNATURE and outputs TRUE or FALSE. The process can be described algorithmically:

1. Output FALSE if SIGNATURE or MESSAGE has an invalid structure.
2. Extract  $\{M, D_i\}$  from MESSAGE
3. Extract  $C$  from CERTIFICATE of SIGNATURE and obtain  $I_0$ . Verify  $C$  for  $M$  and  $I_0$ . Output FALSE if verification fails
4. Extract " $I_0, I_1, I_2, \dots, I_i$ " from IDENTIFIER-LIST of SIGNATURE
5. Extract  $U_i$  from STATIC-PART of SIGNATURE
6. Extract  $Z_i$  from DYNAMIC-PART of SIGNATURE
7. Extract the ordered list of backward link verifiers  $\{W_1, W_2, \dots, W_i\}$  from BACKWARD-LINK-VERIFIER-LIST of SIGNATURE
8. Check that the equality holds:  $e(U_i, P) \stackrel{?}{=} e(V_i, H(M))$ . Output FALSE if not.
9. Check that the equality holds:  $e(W_j, P) \stackrel{?}{=} e(H("I_{j-1}, I_j" \| M), Y_j) \quad \forall j : 1 \leq j \leq i$ . Output FALSE if not.
10. Check that the equality holds:  $e(Z_i, P) \stackrel{?}{=} e(H(D_i \| M), Y_i)$ . Output FALSE if not.
11. Verify that  $M$  and  $D_i$  belong to the same agent (via the mutually authenticating property). Output FALSE if verification fails.
12. Output TRUE

#### 4.3.2 Variant 2

In this scheme,  $I_i$  will use some non-pairing based scheme to sign the dynamic part  $D_i$  and the link verifiers.<sup>9</sup> Let  $\text{SIGN}_i$  represents the secret signing function of  $I_i$  in the non-pairing based scheme (such as RSA). Denote by  $\text{VERIFY}_i$ , the public verification function of  $I_i$  using this different scheme. All the definitions are identical to variant 1 except for  $W_i$  and  $Z_i$  which are redefined as:

$$W_i = \text{SIGN}_i("I_{i-1}, I_i" \| M) \text{ for } i > 0 \text{ and}$$
$$Z_i = \text{SIGN}_i(D_i \| M)$$

---

<sup>9</sup>Note that we still use the pairing based scheme to authenticate the static part.

#### (A) CREATE-CHAIN-SIGNATURE

The only difference in the CREATE-CHAIN-SIGNATURE procedure from the first variant is in steps 9 and 10. The modified steps are:

9. Create DYNAMIC-PART,  $Z_i = \text{SIGN}_i(D_i \| M)$
10. If  $(i > 0)$ , create the new backward link verifier  $W_i = \text{SIGN}_i("I_{i-1}, I_i" \| M)$

#### (B) VERIFY-CHAIN-SIGNATURE

The only difference in the VERIFY-CHAIN-SIGNATURE procedure from the first variant is in steps 9 and 10. The modified steps are:

9. Check that  $\text{VERIFY}_i((D_i \| M), Z_i) = \text{TRUE}$ . Output **FALSE** if not
10. Check that  $\text{VERIFY}_i(("I_{j-1}, I_j" \| M), W_j) = \text{TRUE} \quad \forall j : 1 \leq j \leq i$ . Output **FALSE** if any of the checks fail.

In the next section, we will demonstrate the security of this protocol (both variants).

### 4.4 Correctness and Soundness

In this section, we outline a rough security analysis of our protocol. We consider an attack to be successful if the ordered list of names in the signature contains false information and the verification procedure accepts. Assuming that  $I_i$  is the attacker, a combination of the following attacks are possible:

1. It does not include its name in the list.
2. It adds one or more names to the list.
3. It deletes one or more names from the list or changes the order of names.

We will consider each scenario separately. We note that a detailed security analysis of the protocol is out of the scope of this paper but we also note that the simplicity of the protocol does not demand such analysis.

1. The first possibility is ruled out since otherwise steps 8, 9, 10 and 11 of the verification process will simultaneously fail.
2. Arbitrary names cannot be added to the list because  $I_i$  cannot compute signatures  $M_i$  on behalf of other users. Thus, if a false user is added to the list, step 8 (and/or) 9 of the verification process will fail.
3. Finally deleting names or changing order is not possible either. If the order of participants is changed, the verification process in step 8 will fail with a very high probability.

Thus, we can enumerate the following strong security characteristics of our scheme:

1. Signature Unforgeability: It is not possible for any participant to generate signatures  $U_{(.)}$  for other participants without knowledge of their private keys assuming the hardness of the Bilinear Diffie-Hellman problem (BDHP). Similarly computing any private keys from the public information is will be equivalent to solving the Discrete Logarithm (DL) problem in  $\mathbb{G}_1$  (and consequently  $\mathbb{G}_2$ ).
2. Chained Signature Unforgeability: Similarly it is hard to add arbitrary participants in the chained signatures without knowledge of their public key due to the difficulty of the DL problem.

## 5 Overview of the protocol

The above protocol is an example of a one-way signature chaining scheme. To understand this, see that steps 8 and 9 of the verification process involve the public keys of all participating users (in the right order). Moreover, since  $M$  and  $I_0$  cannot be un-linked due to the certificate  $C$ , it is ensured that a different initial user cannot be used for  $M$ .

We see that the signatures have an “additive” property, demonstrated by the fact that  $I_{i+1}$  can ‘add’ more information to the signature  $U_i$  of  $I_i$  by computing  $U_{i+1}$ . Note that computing any  $U_i$  just from  $U_{i+1}$  is considered infeasible due to the assumed properties of the bilinear map.<sup>10</sup> User  $I_{i+1}$  sends  $U_{i+1}$  as part of the new signature while it keeps  $U_i$  from the old (received) signature as its secret evidence in case of a dispute.

Non-repudiation is provided as follows: (Note that  $I_{i+1}$  must have saved the entire signature **SIGNATURE** of  $I_i$ ).  $I_{i+1}$  can prove in a court that the message **MESSAGE** was indeed received from  $I_i$  by producing this signature as a *witness* and running the **VERIFY-CHAIN-SIGNATURE** procedure.

It is easily seen that the signing time is independent of the number of users. However, the signature length and the verification time increase linearly with the number of users in the list. This is not a problem unless the list becomes very large. Assuming that all users are unique, a few points about this protocol are noteworthy:

1. Each  $I_i$  who passes the message must include its name in the signature and in the right sequence for validation to succeed.
2. Users cannot remove names of other users from the list in the signature without knowledge of their private keys, nor can they change the order or add new names.
3. Authentication is relative to  $I_0$  who in turn authenticates with the TTP. If, however, it is possible to establish the originator of a message directly from its contents or by some other means, the TTP can be eliminated. For a discussion on this see [9].

---

<sup>10</sup>Observe that  $U_i$  cannot be computed from  $U_{i+1}$  without knowledge of  $x_i$  but knowledge of  $U_i$  does not reveal  $x_i$ .

4. The signing and verification procedures are completely non-interactive.
5. The dynamic part is only authenticated to the previous hop. The itinerary authentication is done entirely using the static part.

If we consider the message without the dynamic part, we get a simple signature-chaining protocol for message passing, with the message being  $M$ , the static part. For all the applications discussed in the next session, we assume that **MESSAGE** is simply the static part and the signing and verification procedures and the signature structure are accordingly modified to exclude all references to the dynamic part (in other words, step 9 of the signing process and steps 6, 10 and 11 of the verification process are excluded).

## 6 Applications of Signature Chaining

In this section, we list several applications of signature chaining. The concept of signature chaining was originally proposed for mobile agent authentication [9, 10], electronic auctions, proxy signatures [32] and digital cash [33] but without any practical examples.

Considering that one-way signature chaining enables us to correctly validate path of any received message and provides non-repudiation, we can consider various other applications: group e-commerce (e-commerce transactions where multiple entities are involved such that direct interaction is not possible between many of them), electronic work-flow enforcement (ensuring the order in which participants should be involved), ‘secret-passing’ protocols, secure routing, authenticated mail relaying and spam tracing, token based authentication, IP tracing, mobile IP, intrusion detection, GRID computing, battlefield modeling, Supply Chain Management, distributed systems and wireless roaming.

## 7 Conclusion

In this paper, we proposed an authentication protocol for mobile agents based on bilinear pairings over elliptic curves. Our method is based on the notion of additive zero knowledge [9] which enables trust to propagate between different provers. We demonstrated that signature chaining can be used to form ad-hoc trust relationships between multiple participants in a dynamic and non-interactive manner. Our protocol can be used to authenticate the itinerary of mobile agents without any active involvement of a Trusted Third Party (TTP). It may be possible to completely eliminate the TTP using methods of code obfuscation, watermarking and undetachable signatures. We note that the size of signatures and the verification time increase linearly with the number of users. A further improvement would be to try to find schemes where the verification time and signature size is constant. Finally, it is worth researching if a certificate-less or an identity based scheme can be derived from the certificate based one presented in this paper.

## References

- [1] David Kotz and Robert S. Gray. Mobile agents and the future of the internet. *SIGOPS Oper. Syst. Rev.*, 33(3):7–13, 1999.
- [2] Tomas Sander and Christian F. Tschudin. Protecting mobile agents against malicious hosts. *Lecture Notes in Computer Science*, 1419:44–60, 1998.
- [3] Joy Algesheimer, Christian Cachin, Jan Camenisch, and Günter Karjoth. Cryptographic security for mobile code. In *SP '01: Proceedings of the IEEE Symposium on Security and Privacy*, pages 2–11. IEEE Computer Society, 2001.
- [4] Panayiotis Kotzanikolaou, Mike Burmester, and Vassilios Chrissikopoulos. Secure transactions with mobile agents in hostile environments. In *Australasian Conference on Information Security and Privacy*, volume 1841, pages 289–297, Australia, 2000. Springer-Verlag.
- [5] Joris Claessens, Bart Preneel, and Joos Vandewalle. (how) can mobile agents do secure electronic transactions on untrusted hosts? a survey of the security issues and the current solutions. *ACM Trans. Inter. Tech.*, 3(1):28–48, 2003.
- [6] Bennet S. Yee. A sanctuary for mobile agents. In *Secure Internet Programming*, pages 261–273, 1999.
- [7] U. G. Wilhelm, S. Staamann, and L. Buttyán. Introducing trusted third parties to the mobile agent paradigm. In J. Vitek and C. Jensen, editors, *Secure Internet Programming: Security Issues for Mobile and Distributed Objects*, volume 1603, pages 471–491. Springer-Verlag, New York, NY, USA, 1999.
- [8] G. Karjoth, D.B. Lange, and M. Oshima. A security model for aglets. *IEEE Internet Computing*, 1(4):68–77, 1997.
- [9] Amitabh Saxena and Ben Soh. Authenticating mobile agent platforms using signature chaining without trusted third parties. In *Proceedings of The 2005 IEEE International Conference on e-Technology, e-Commerce and e-Service (EEE-05)*, pages 282–285, Hong kong, 2005. IEEE computer press.
- [10] Amitabh Saxena and Ben Soh. A novel method for authenticating mobile agents with one-way signature chaining. In *Proceedings of The 7th International Symposium on Autonomous Decentralized Systems (ISADS 05)*, pages 187–193, China, 2005. IEEE Computer Press.
- [11] Dan Boneh and Matthew K. Franklin. Identity-based encryption from the weil pairing. In *CRYPTO '01: Proceedings of the 21st Annual International Cryptology Conference on Advances in Cryptology*, pages 213–229. Springer-Verlag, 2001.
- [12] Sattam S. Al-Riyami and Kenneth G. Paterson. Certificateless public key cryptography. *Cryptology ePrint Archive*, Report 2003/126, 2003.
- [13] K. Paterson. Id-based signatures from pairings on elliptic curves.
- [14] Song Han, Winson K.Y. Yeung, and Jie Wang. Identity-based confirmer signatures from pairings over elliptic curves. In *EC '03: Proceedings of the 4th ACM conference on Electronic commerce*, pages 262–263, New York, NY, USA, 2003. ACM Press.
- [15] X. Chen, F. Zhang, and K. Kim. A new id-based group signature scheme from bilinear pairings, 2003.
- [16] J. Cha and J. Cheon. An identity-based signature from gap diffie-hellman groups.

- [17] F. Zhang and K. Kim. Id-based blind signature and ring signature from pairings, 2002.
- [18] Amit K Awasthi and Sunder Lal. Id-based ring signature and proxy ring signature schemes from bilinear pairings. Cryptology ePrint Archive, Report 2004/184, 2004.
- [19] Florian Hess. Efficient identity based signature schemes based on pairings. In *SAC '02: Revised Papers from the 9th Annual International Workshop on Selected Areas in Cryptography*, pages 310–324, London, UK, 2003. Springer-Verlag.
- [20] Antoine Joux. A one round protocol for tripartite diffie-hellman. In *ANTS-IV: Proceedings of the 4th International Symposium on Algorithmic Number Theory*, pages 385–394, London, UK, 2000. Springer-Verlag.
- [21] Shanshan Duan, Zhenfu Cao, and Rongxing Lu. Robust id-based threshold sign-cryption scheme from pairings. In *InfoSecu '04: Proceedings of the 3rd international conference on Information security*, pages 33–37, New York, NY, USA, 2004. ACM Press.
- [22] Eric R. Verheul. Self-blindable credential certificates from the weil pairing. In *ASIACRYPT '01: Proceedings of the 7th International Conference on the Theory and Application of Cryptology and Information Security*, pages 533–551, London, UK, 2001. Springer-Verlag.
- [23] N. Smart. An identity based authenticated key agreement protocol based on the weil pairing.
- [24] Dan Boneh, Ben Lynn, and Hovav Shacham. Short signatures from the weil pairing. In *ASIACRYPT '01: Proceedings of the 7th International Conference on the Theory and Application of Cryptology and Information Security*, pages 514–532, London, UK, 2001. Springer-Verlag.
- [25] Paulo S. L. M. Barreto, Hae Yong Kim, Ben Lynn, and Michael Scott. Efficient algorithms for pairing-based cryptosystems. In *CRYPTO '02: Proceedings of the 22nd Annual International Cryptology Conference on Advances in Cryptology*, pages 354–368, London, UK, 2002. Springer-Verlag.
- [26] Christian S. Collberg and Clark Thomborson. Watermarking, tamper-proofing, and obfuscation - tools for software protection. *IEEE Transactions on Software Engineering*, 28(8):735–746, August 2002.
- [27] Chenxi Wang, Jonathan Hill, John Knight, and Jack Davidson. Software tamper resistance: Obstructing static analysis of programs. Technical report, University of Virginia, University of Virginia, 2000.
- [28] Julien P. Stern, Gael Hachez, Francois Koeune, and Jean-Jacques Quisquater. Robust object watermarking: Application to code. In *Information Hiding*, volume 1768, pages 368–378, Germany, 1999. Springer-Verlag.
- [29] Boaz Barak, Oded Goldreich, Russell Impagliazzo, Steven Rudich, Amit Sahai, Salil Vadhan, and Ke Yang. On the (im)possibility of obfuscating programs. Cryptology ePrint Archive, Report 2001/069, 2001.
- [30] Z. Cheng, L. Vasiu, and R. Comley. Pairing-based one-round tripartite key agreement protocols, 2004.
- [31] Ratna Dutta, Rana Barua, and Palash Sarkar. Pairing-based cryptographic protocols : A survey. Cryptology ePrint Archive, Report 2004/064, 2004.

- [32] Chunbo Ma. Proxy chain signature. Unpublished Manuscript, 2005.
- [33] Amitabh Saxena, Ben Soh, and Dimitri Zantidis. A digital cash protocol based on additive zero knowledge. In *Proceedings of The 3rd International Workshop on Internet Communications Security (ICCSA 05)*, volume 3482 of *Lecture Notes in Computer Science*, pages 672–680, Singapore, 2005. Springer-Verlag.