A Public-key based Information Management Model for Mobile Agents

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Abstract — Mobile code based computing requires development of protection schemes that allow digital signature and encryption of data collected by the agents in untrusted hosts. These algorithms could not rely on carrying encryption keys if these keys could be stolen or used to counterfeit data by hostile hosts and agents. As a consequence, both information and keys must be protected in a way that only authorized hosts, that is the host that provides information and the server that has sent the mobile agent, could modify (by changing or removing) retrieved data. The data management model proposed in this work allows the information collected by the agents to be protected against handling by other hosts in the information network. It has been done by using standard public-key cryptography modified to support protection of data in distributed environments without requiring an interactive protocol with the host that has dropped the agent. Their significance stands on the fact that it is the first model that supports a full-featured protection of mobile agents allowing remote hosts to change its own information if required before agent returns to its originating server.

Keywords — Assurance, Asymmetric ciphers, Cryptography, Data protection, Distributed networks, Information retrieval, Mobile agents.

I. INTRODUCTION

GLOBAL-NETWORKING and world-wide communications are changing computing concepts as were established some years ago. In the past, information was stored in trusted hosts where data was managed. In that case, it is easy to see that information security depends on the protection of the hosts themselves. Protection of hosts should be considered as a part of the operating systems design and not as an add-on. In fact, to ignore last approach opens a wide variety of security holes in modern computer systems 1. In any case, hosts protection is more advanced that mobile code protection at present time. Distributed computing requires information to be managed in untrusted —and sometimes unknown— hosts in the network; consequently, new data management models must be developed for distributed environments 2, 3.

Some protection schemes based in the use of Partial Result Authentication Codes (PRACs) ensures a perfect forward integrity but does not assures backward integrity 1. In these cases, the mobile agent carries the keys that will be used to protect the messages. Each key could be applied to protect only one message being removed from the agent data area after using. Even forward integrity could be compromised. For example suppose that an agent follows a route $\mathcal{H} = \{H_1, H_2, \ldots, H_n\}$, where both $H_1^*$ and $H_2^*$, with $i, j \in \{1, 2, \ldots, n\}$ and $i < j$, are malicious hosts. The first hostile node in the route of the agent, that is $H_1^*$, could provide a copy of the keys not removed from the mobile agent to the second malicious host, $H_2^*$. The second host could use this information to counterfeit data provided by the hosts that apply these keys. This fact makes all the hosts in the subset $\mathcal{H}' = \{H_2^*, H_3^*, \ldots, H_n^*\} \subset \mathcal{H}$ vulnerable. The same problem will happen if the agent returns to the first malicious host later, showing that backward integrity cannot be assured in any case.

The term message, as applied in this paper, stands for each block of information provided by the remote hosts to either other hosts or mobile agents. The word field identifies a chunk of the message itself.

We want to note some differences that can be found between mobile agents, mobile code and intelligent agents, to show in detail the problem that could be solved by using the threat described in our work:

- **Mobile agents.** A mobile agent is a software object that have a code area and a data part. Both code and data areas will convey from a host to another one but the execution thread will not be preserved. Mobile agents could be easily implemented by using serialization in programming languages as Java.

- **Mobile code.** The most important difference between mobile agents and mobile code is that the latter allows the execution thread to be preserved when the agent goes from one host to the next one. As the execution thread will be changed in each host visited by the mobile code, to protect this area is not easy.

- **Intelligent agents.** An intelligent agent is a software object that have the ability of process information retrieved autonomously. These agents does not require to be mobile. Intelligent agents are an active field of study in artificial intelligence (AI) at present.

A given agent could be classified in more than one of the groups described above. For example, a mobile agent could be programmed in a way that allows it to decide the route that it will follow by evaluating the information provided by the peer (remote) hosts, making it both a mobile and an intelligent agent simultaneously.

The threat we propose in our work allows an agent to be protected against both malicious hosts and other agents. These hosts and agents could try to make unauthorized modifications on either the code area or the data space...
of the agent or even to remove the information provided by other hosts. Our goal is to protect code and data areas against both counterfeit and erasing. Our technique is based in the use of standard public-key encryption algorithms—a also known as asymmetric encryption—instead of symmetric ciphers. We will not propose nor recommend the use of a specific cipher other works in our work.

We are not developing a protection algorithm for the execution thread. The execution thread is changed by each host where the mobile code arrives. As a consequence, it cannot be easily protected without using a logging system. In our opinion, encryption techniques could not be used to provide full protection of mobile code.

II. NOTATIONAL CONVENTIONS

In this section, we will introduce the notation used in our work. This notation will be applied to describe digital signature and encryption of data in both the agent server and the peer hosts.

To describe the routes followed by the agents we will define the set \( H^r = \{ H^r_1, H^r_2, \ldots, H^r_{n_r} \} \), where \( r = 1, 2, 3, \ldots \) and \( n_r \in \mathbb{N} \); this set will denote the \( n_r \) hosts followed by the mobile agent released by a given agent server in its \( r \)-th route. In this set, \( H^r_i \), where \( i \in \{ 1, 2, \ldots, n_r \} \) and \( r \in \mathbb{N} \), determines the \( i \)-th host in the \( r \)-th route followed by the agent sent by the server \( S \).

Digital signature—Digital signature of data can be used to protect the information provided against counterfeit and erasing by allowing, at the same time, to be read and authenticated by other hosts. It could be useful when agents are used in negotiation processes between hosts. In this case, only the private/public key pairs related with the remote hosts are used to protect the data stored in the agents allowing the information to be read and authenticated by any host or agent without a knowledge of the private-key used to digitally sign the message. We will denote the digital signature of any given message \( M^r_{i,j} \) using the expression:

\[
S^r_{i,j} \equiv f_{\text{pri}_{H^r_j}}[M^r_{i,j}],
\]

where \( M^r_{i,j} \) and \( S^r_{i,j} \) are the plain-text message and its signature respectively, \( \text{pri}_{H^r_j} \) identifies the private-key associated with the host \( H^r_j \) and \( f \) stands for the digital signature algorithm applied to protect the information provided by the peer hosts against unauthorized modifications.

The message \( M^r_{i,j} \) can be authenticated by using the public-key associated with the \( i \)-th host in the agent route \( H^r \). That public-key may be available to any host. The security of the host \( H^r_j \) is not compromised by storing a copy of that public-key in a public-key server. As we will shown below, the use of certification authorities (CAs) to authenticate the public-keys itself is highly recommended. We must apply

\[
M^r_{i,j} = f_{\text{pub}_{H^r_j}}^{-1}[S^r_{i,j}],
\]

where \( M^r_{i,j} \) and \( S^r_{i,j} \) are the plain-text message and the digital signature of \( M^r_{i,j} \) again, \( \text{pub}_{H^r_j} \) stands for the public-key associated with the host \( H^r_j \) and \( f^{-1} \) identifies the digital signature authentication algorithm.

Data encryption—A mobile agent based infrastructure would require an additional security level. Suppose that a server drops an agent that will retrieve information that must be covered to any host in the network except the server that has released the agent itself. In this case, data encryption should be used to hide the information stored in the agent data area. Data encryption requires the use of an additional key pair, the private/public key pair related with the agent server. Encryption of data requires the use of the public-key provided by the agent server to the remote hosts as a part of the mobile agent itself (\( \text{pub}_S \)), and the private-key associated with the remote host that provides information to the agent. We will show below that the private/public key pair related with the server that has released the agent cannot be counterfeited without invalidating the agent itself because it is a part of the code area. We will define the encryption process as:

\[
C^r_{i,j} \equiv f_{\text{pub}_S}[f_{\text{pri}_{H^r_i}}[M^r_{i,j}]].
\]

In this case, \( M^r_{i,j} \) and \( C^r_{i,j} \) are the plain-text message and its cipher-text respectively. The symbols \( \text{pub}_S \) and \( \text{pri}_{H^r_i} \) in equation (3) stand for the public-key related to the agent server \( S \) and the private-key associated with the \( i \)-th host in the \( r \)-th route followed by an agent dropped by the server \( S \) respectively. In order to decrypt the cipher-text we must use the private-key associated with the agent server (\( \text{pri}_S \)), and the public-key provided by the peer host that has encrypted the message \( M^r_{i,j} \):

\[
M^r_{i,j} = f_{\text{pub}_{H^r_i}}^{-1}[f_{\text{pri}_S}^{-1}[C^r_{i,j}]]
\]

\[
= f_{\text{pub}_{H^r_i}}^{-1}[f_{\text{pri}_S}^{-1}[f_{\text{pub}_S}[f_{\text{pri}_{H^r_i}}[M^r_{i,j}]]]].
\]

The elements that appear in equation (4) must be interpreted in the same way as shown in other equations in this section. In this case, \( \text{pri}_S \) and \( \text{pub}_S \) are, respectively, the private and the public keys for the agent server; \( \text{pri}_{H^r_i} \) and \( \text{pub}_{H^r_i} \) are the private and the public keys for the remote host \( H^r_i \). The message that has been covered by using public-key cryptography is \( M^r_{i,j} \), that is the \( j \)-th message provided by the \( i \)-th host in the route followed by the agent, and the cipher-text itself is \( C^r_{i,j} \).

III. CODE AND DATA AREAS PROTECTION

Classical protection schemes do not allow a mobile agent to protect its own code area against unauthorized modifications easily. Suppose that a server digitally signs the code of an agent before dropping it. This server must provide copies of the public-key used to other hosts. This public-key is required to authenticate the code area itself. This can be done easily by providing a copy of this key to a key-server or by using a CA. Obviously, the agent should be instructed to get this key showing at least the address of both the server that has released it and the host that stores a copy of the key. At this moment a malicious host, let us
say $H^r_i$, could change the agent code area and sign it by using its own private/public key pair. It is not difficult to prove that this modification will not be discovered by the remote hosts if the code is changed in such a way that the agent points to the new public-key. The hostile host only needs to assure that the signed code area provided by the agent server is recovered before the agent returns to the server that has dropped it.

It is easy to see that code protection could not depend on classical cryptography even if the keys used to authenticate this area are certified and are provided by external trusted authorities. We need to develop a way to link the data provided by the peer hosts with the code part of the agent at the same time. This will allow us to protect data and code areas simultaneously.

Other protection threats have been proposed in recent years. For example, the use of both code and data areas mess up techniques as described in [6]. In this reference, Hohl recommends the use of variable names that does not mean anything. He also proposed that the code should not be modularized (i.e., it must be written without using subroutines) and to choose a data representation that makes the program difficult to understand. This author proposed the use of variable recomposition techniques, conversion of compile-time control flow elements into run-time data dependent jumps and the insertion of dead code, that is code that will not be executed when the agent is running, into the agents. These techniques are based in mixing up the contents of the variables and creating new variables that contains a few bits of data of some of the original variables. These are recovered by changing the way the code of the agent handles the access to the variables. Another alternative could be to develop a secure infrastructure for mobile agents [6]. The use of encrypted functions and execution environments (EE) with a fully separated interpreter has been proposed in [6]. At present, we do not have a way of protecting the code against unauthorized modification using encrypted functions because these techniques could not be easily applied to real agent systems. We need protection schemes that do not rely on hiding the algorithms used in code handling or on building trusted environments for agent execution. Another problem is that the execution of encrypted functions requires the development of one-way homomorphic functions. These functions are unknown at present.

In order to protect both the message provided by the remote host, that we have denoted by $M^r_{i,j}$, and the mobile agent code area we propose that each host must obtain the next field:

$$M^r_{CRC_{i,j}} \defeq \text{crc}[\text{pubs}] + \text{crc}[f_{\text{pri}_i}[M^r_{\text{code}}]] + F^r_{i,j},$$

where $f_{\text{pri}_i}[M^r_{\text{code}}]$ stands for the digital signature of the code area $M^r_{\text{code}}$. The code area includes both the agent code and an identification number (ID) for the agent. Therefore, this identification number is unique because it is generated from the agent server identifier, which is unique in the network (for example the IP-address in IPv4 or IPv6 format of the agent server itself), and an agent number, which is unique for that server. In our case, we will obtain $ID = serverID + agentID$. Obviously, $f_{\text{pri}_i}[M^r_{\text{code}}]$ could not be evaluated in the remote hosts. To obtain this field, a knowledge of the private-key associated with the server that has dropped the agent ($\text{pri}_i$) is required. This field must be provided as a part of the agent in a way that cannot be falsified. To manage it, a field $F^r_{i,j}$ must be added by the host $H^r_i$ to the field $M^r_{CRC_{i,j}}$ shown in equation (5). This field must change with each message provided in a way that it is unique for that host/agent pair. The code part must be authenticated by comparing its digital signature with the signature carried by the agent by each peer host before accepting it. The cyclic redundancy check (CRC) of both the public-key associated with the agent server and the signature of the agent code in (3) can be obtained by each remote host by using a hash algorithm. This information must be matched with the CRCS of both the public-key of the agent server and the digital signature provided as a part of the data area.

In this section the term improved (as appears in both improved digital signature and improved data encryption) stands for digital signature and encryption processes that include information about the mobile agent code area. In fact, information about the code part of the agent will be included by each peer host in the field $M^r_{CRC_{i,j}}$, as shown in equation (5), allowing remote hosts to detect unauthorized modifications of the code part of the agents. Partial data encryption will also provide a signed copy of the field $M^r_{CRC_{i,j}}$. In this case, both the field $M^r_{CRC_{i,j}}$ and the message $M^r_{i,j}$ will be digitally signed but only the message $M^r_{i,j}$ itself will be encrypted, allowing each host to detect code tampering but protecting information against reading by unauthorized hosts at the same time.

**Improved digital signature** — In our opinion it is possible to protect both the agent code area and the information provided by the host itself simultaneously. To manage it, the field $M^r_{CRC_{i,j}}$ must be used. This field must be stored as a part of each message provided to the mobile agents before being digitally signed:

$$S^r_{i,j} = f_{\text{pri}_i}^r \left[ M^r_{CRC_{i,j}} + M^r_{i,j} \right];$$

this step assures data integrity while avoiding the possibility to overwrite a new message provided by a remote host with an old one provided to another mobile agent in the

$^1$By using mathematical functions with homomorphic properties. An example is the exponential function where the addition and mixed multiplication between $x, y \in \mathbb{C}$ could be obtained without any explicit knowledge of $x$ providing $\exp[x + y]$ instead of $x$ in:

$$\exp[x + y] = \exp[x] \cdot \exp[y]$$

$$\exp[x \cdot y] = (\exp[x])^y,$$

allowing us to represent the encrypted program as a polynomial. An important requirement is that these functions should not be easily inverted. At present, there are not known one-way homomorphic functions.

$^2$Where each agent have its own address space.
past. The information protected in this way is authenticated by applying the public-key $\text{pub}_{H_i'}$ of the host that has signed it:

$$M_{\text{CRC}_{i,j}} + M_{i,j} = f^{-1}_{\text{pub}_{H_i'}} [S_{i,j}]$$

$$= f^{-1}_{\text{pub}_{H_i'}} [f_{\text{pri}_{H_i'}} [M_{\text{CRC}_{i,j}} + M_{i,j}]].$$

**Improved data encryption**—The information about the code area of the mobile agent obtained by using the host is added to the message provided by the remote host. To encrypt a message for the agent server we must apply the next algorithm to the message itself:

$$C_{i,j} = f_{\text{pub}_{H_i'}} [f_{\text{pri}_{H_i'}} [M_{\text{CRC}_{i,j}} + M_{i,j}]].$$

In order to recover the full message, $M_{\text{CRC}_{i,j}} + M_{i,j}$, the agent server should apply its own private-key, $\text{pri}_{H_i'}$, and the public-key provided by the host that has encrypted the message, $\text{pub}_{H_i'}$, obtaining:

$$M_{\text{CRC}_{i,j}} + M_{i,j} = f^{-1}_{\text{pub}_{H_i'}} [f^{-1}_{\text{pri}_{H_i'}} [C_{i,j}]].$$

The main disadvantage of this method is that the code can be counterfeited in such a way that only the agent server knows that it has been falsified. If a part of $C_{i,j}$ is not encrypted, but is digitally signed, all the hosts in the route of the agent will have a way to determine whether the code area or other data in the agent have been falsified by any host.

**Partial data encryption**—A better answer to the problem of data encryption is to provide information publically about the CRC of both the public-key related with the agent server ($\text{pub}_{H_i}$) and the signature of the agent code, $f_{\text{pri}_{H_i}} [M_{\text{code}}]$. It is possible to do it and, at the same time, to hide the message in such a way that only the authorized host (the agent server) could decrypt it. We propose to partially encrypt a digitally signed message using:

$$C_{i,j} = f_{\text{pri}_{H_i}} [M_{\text{CRC}_{i,j}} + f_{\text{pub}_{H_i}} [M_{i,j}]].$$

The main disadvantage of this method is that the code can be counterfeited in such a way that only the agent server knows that it has been falsified. If a part of $C_{i,j}$ is not encrypted, but is digitally signed, all the hosts in the route of the agent will have a way to determine whether the code area or other data in the agent have been falsified by any host.

**Public-key Propagation**

One of the main goals of our work is to provide a threat that allows mobile agents to be protected against attacks like those described in Section V-A. We propose to use public-key ciphers, also known as asymmetric cryptosystems, instead of symmetric ciphers because the latter allows a simplified key management in distributed environments. Public-keys can be shared between hosts in a network without requiring secure communication channels like those obtained using, for example, the Transport Layer Security (TLS) protocol. Detailed information about the TLS protocol can be found in [8], [9].

Some important requirements must be considered in the development of a public-key propagation infrastructure for mobile agents:

- **Certification authorities.** It is easy to see that uncertified public-keys cannot be trusted. It is not a good practice to send keys directly to the servers that need them. We need a network infrastructure that allows the nodes to assure what host owns each private/public key pair. For example, middleman attack, the greatest known vulnerability of public-key based ciphers, can be avoided by using a trusted third party to verify and sign the keys transmitted over the network.

- **Non-interactive protocol.** As pointed out it is easy to see that unceterified public-keys cannot be trusted. It is not a good practice to send keys directly to the servers that need them. We need a network infrastructure that allows the nodes to assure what host owns each private/public key pair. For example, middleman attack, the greatest known vulnerability of public-key based ciphers, can be avoided by using a trusted third party to verify and sign the keys transmitted over the network.

- **Secure communication channels are not required.** This is a common advantage of public-key cryptography. As only public-keys are transmitted over the network untrusted communication channels can be established to share the keys. These keys cannot be used to falsify information or decrypt data provided to the agents.

- **We do not need to know what host owns each public-key.** Obviously, this fact is only true if different access privileges are not assigned to each agent in function of the server that has released it. If different access permissions are required CAs must be used to authenticate the keys provided to the remote hosts and to assign the right access privileges to each agent server.

Certified public-keys are required even if different access permissions are not assigned to mobile agents in function of the server that has dropped it. In fact, each peer host must identify other hosts in the network in soon a way that it does not allows host impersonation techniques. Trusted
third parties are needed to avoid well known threats like the middleman attack. We must consider that changing the public-keys carried by mobile agents —the public-keys associated with the agents servers— will invalidate data retrieved by the agents. If the information stored in the mobile agent data area is removed from the agent when this public-key is falsified other hosts will not have a way to determine that the agent have been modified without authorization. But this fact will be discovered by the agent server after the agent return. These keys do not require to be authenticated using a CA. Changing public-key for a given agent must be avoided once they have been provided to the route servers (RSs).

As we noted in Section III, both code and data areas can be protected against counterfeiting and erasing by malicious hosts and agents. This can be achieved by adding a field $M_{\text{CRC}}^{i,j}$ to each message retrieved by a mobile agent as presented in (3). This field, $M_{\text{CRC}}^{i,j}$, will provide information about both the code part of the agent and the public-key of its originating server. This field will be stored in such a way that it does not allow changing the code of the agent without invalidating it.

Each agent have its own ID to avoid the possibility of overwriting the information provided by peer hosts with old data retrieved by other agents sent by the same server. This field is stored as a part of the code area. As a consequence, $\text{crc}[f_{\text{pri}}[M_{\text{code}}]]$ changes when new agents are dropped. Even obsolete information provided to the same agent in the past cannot be used to cover new data. Each host must generate a field, we called $F^r_{i,j}$, unique for each message. All these fields should be sent to the RSs:

$$F^r_i = \text{ID} + F^r_{1,1} + F^r_{1,2} + \ldots + F^r_{1,m^r_i} = \text{ID} + \sum_{j=1}^{m^r_i} F^r_{i,j} ,$$

(13)

where ID is the agent identification number mentioned above. The field $F^r_i$ must be sent to RSs digitally signed by applying:

$$S_{\text{fields}_i} = f_{\text{pub}_{H^r_i}}[F^r_i] ,$$

(14)

using the private/public key pair for the host that provides that information. Any host can check each message provided by $H^r_i$ by using the $F^r_{i,j}$ fields, where $i \in \{1, 2, \ldots, n_r\}$ and $j = 1, 2, \ldots, m^r_i$, stored in $F^r_i$. Those fields must be authenticated by using:

$$F^r_i = f_{\text{pub}_{H^r_i}}^{-1}[S_{\text{fields}_i}] = f_{\text{pub}_{H^r_i}}^{-1}[f_{\text{pri}_{H^r_i}}[F^r_i]] .$$

(15)

To assure the integrity of the message $F^r_i$ each RS should send a random message to the host that wants to provide a new (or an updated) message $F^r_i$. This random message must be digitally signed and returned to the RS that released it. The random message signature must be checked before the RS accepts $F^r_i$. In other case, a malicious host can provide an obsolete message $F^r_i$ to the RSs overwriting the mobile agent data area with old information corresponding to the false message $F^r_i$ simultaneously.

V. ATTACKS AGAINST MOBILE AGENTS INFRASTRUCTURES

In this section we classify the attacks that is possible to try against the mobile agents and other hosts in the network. We show how our protection threat allows us to protect the agents and, in some cases, even remote hosts against these attacks.

A. Attacks against Mobile Agents

The main goal of our investigation is to protect the mobile agents against both malicious hosts and other agents that can counterfeit the code part and/or data areas of the agents. These hostile agents and hosts can try to remove information carried by the agents too. As noted, these attacks could arrive from both other agents and the hosts where the agents are stored. In both cases, we will protect the agent using the same threat.

A.1 Attacks against the Code Part

As we shown in Section III the agent code area can be protected by adding two CRCs to each message provided by the peer hosts. These CRCs provides information that allows peer hosts to authenticate both the public-key associated with the agent server and the digital signature of the code area of the agent, that has been provided by the agent server itself. These fields must be matched with each message stored in the data area by the hosts followed in the agent trip, as appears in the set $H^r$. At last, each host authenticates the code area of the agent too before running it using that digital signature previously checked. As both the CRC related with the digital signature of the code area and the CRC for the public-key of the agent server cannot be changed during agent trip, but the latter is unique for a given agent, data area is protected at the same time. As a consequence, the attacks described below can be avoided.

A.2 Attacks against the Data Area

The attacks against the information carried by mobile agents can be classified in three groups: (i) attacks trying to erase data carried by the agents (also known as a mobile agent “brainwashing” in bibliography), (ii) attacks trying to falsify data provided by other hosts and (iii) attacks trying to uncover non-public information carried by the agents.

Removing information—To avoid a mobile agent “brainwash” each host must provide information about the number of messages stored in a particular agent to the RSs as we described in Section IV. It is easy to see that all the information needed to protect the data area cannot be stored in the agent. Suppose for example that a mobile agent carries a set of signed messages

$$\mathcal{D}^r = \{S^r_{1,1}, S^r_{1,2}, \ldots, S^r_{1,m^r_1}, S^r_{2,1}, S^r_{2,2}, \ldots, S^r_{2,m^r_2}, \ldots, S^r_{n_r,1}, S^r_{n_r,2}, \ldots, S^r_{n_r,m^r_{n_r}}\} ,$$

(16)

in its data area. The set $\mathcal{D}^r$ in (16) stands for the signed data area of the $r$-th agent released by a server. All the
messages are signed in a way that only the hosts that has provided these messages can change its contents. If the RSs do not provide information about the number of messages given by each host to the agent server or, more generally to other hosts that requests it, any hostile node (any malicious host in the network) can remove a message, let us say $S_{i,j}$, where $i \in \{1,2,\ldots,n_r\}$ identifies the host that provides the message removed and $j \in \{1,2,\ldots,m_i\}$ stands for the $j$-th message provided by that host. In this case, the set of messages carried by the agent, $D'$, is changed to

$$D'^{r} = \{S'_{1,1}, S'_{1,2}, \ldots, S'_{1,m_1}, S'_{2,1}, S'_{2,2}, \ldots, S'_{2,m_2}, \ldots, S'_{n_r,1}, S'_{n_r,2}, \ldots, S'_{n_r,m_{n_r}} \},$$

without invalidating the data area. In this case, the set $D'^{r}$ is the falsified data area of the agent. The same problem happens when encryption is used if the number of messages carried by a mobile agent is not provided to the RSs in any way. In this case the encrypted data area of the agent:

$$D' = \{C_{r,1,1}, C_{r,1,2}, \ldots, C_{r,m_1}, C_{r,2,1}, C_{r,2,2}, \ldots, C_{r,m_2}, \ldots, C_{r,1,n_r}, C_{r,2,n_r}, \ldots, C_{r,m_{n_r}} \},$$

(17)

can be modified by removing one of the cipher-texts provided by the remote hosts. For example, the cipher-text that corresponds to the $j$-th message provided by the $i$-th host in the agent route can be erased by changing the agent data area to:

$$D'^{r} = \{C'_{r,1,1}, C'_{r,1,2}, \ldots, C'_{r,m_1}, C'_{r,2,1}, \ldots, C'_{r,2,m_2}, \ldots, C'_{r,1,n_r}, C'_{r,2,n_r}, \ldots, C'_{r,m_{n_r}} \}.$$
A.3 Attacks against the Agents itself

The mobile agents can be attacked in a way that do not require to modify either the code area or the data part of the agents. The main goal of these attacks can be to damage the agent infrastructure itself by destroying the agents or releasing new agents instead of the original one.

Removing agents— Any malicious host can remove the agents when arrive to it. There are no-way to avoid this attack against the agents but or protection threat allows other host to try to discover what host has killed the agent by requesting information about the route followed by the agent.

Releasing new agents— A hostile host can remove all the information stored in the mobile agent and change the code area. Modifying the code area requires gathering a fake private/public key pair for the agent server but now it is possible because all the $M_{CRC,j}$ fields have been removed from the data area of the agent. The new private/public key pair can be used to sign a modified code area of the agent. This fact can be discovered, at least, by the server that has released the agent when it comes back. If other hosts have a copy of the public-key of the agent server, either obtained by other channels or sent in the past, these hosts can discover the unauthorized modification of the agent too.

B. Attacks against Peer Hosts

Our goal is to protect mobile agents against attacks from both peer hosts and other agents. We are not trying to develop a threat to protect hosts against malicious agents. Attacks against remote hosts could be initiated from both agents and hosts.

The code area protection allows an agent to be protected against malicious changes that could affect how it works. At the same time, the code protection allows a host to be protected against Denial of Service (DoS) attacks by agent cloning in the sense that the number of clones could be easily verified by using the agent identification number described above. This allows a host to protect itself by controlling the resources provided to the agents in a per-agent basis. The agent identification number allows a host to identify the number of clones of a given agent.

The code protection threat proposed in our work do not permits a hostile host to change the code part of an agent provided by an agent server without invalidating it but, obviously, this host could release its own malicious agents.

VI. Conclusions

Mobile agents are an extremely vulnerable piece of software because they are executed in untrusted environments. Both code and data areas must be protected against malicious hosts and agents. The former requires techniques that does not allow a malicious host to hide the identity of the real agent owner. The latter requires information provided by remote hosts to be protected against counterfeite and erasing. The main advantages of the algorithm proposed in this paper are that:

- **Secure communication channels are not required** allowing a mobile agent to be transmitted over untrusted channels and even stored in malicious hosts where the agent will be shown as plain-text even if trusted communication channels between hosts are established.
- **Both code and data areas are protected** against counterfeite and erasing; consequently, mobile agents are a more secure and robust platform.
- **Each host could change its own information** when required. This allows a host to update information provided permitting the development of more sophisticated agent-based applications, where negotiation between agents and hosts is required.

We hope that our protection scheme allows mobile agent based infrastructures to be protected against other attacks based on threats not covered in this article or even unknown at present. If this can be achieved, our threat could be a good design principle for mobile agent based information networks.

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