VERIFICATION AND ANALYSIS OF AN IMPROVED AUTHENTICATION PROTOCOL FOR MOBILE IP

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Abstract

In this paper, we proposed an authentication protocol for Mobile IP to improve its scalability and efficiency. The protocol was verified and analysed with BAN logic. We discovered that there is a tradeoff between security and efficiency. To improve the efficiency, we omitted the direct authentication between the Mobile Host (MH) and the Foreign Agent (FA) which resulted in weaker beliefs. However, through discussion, we were able to show that the result does not compromise the security of the protocol.

Keywords:

Mobile IP, Scalable Tripartite Authentication, public-key cryptographic mechanism, secret-key cryptographic mechanism, BAN logic.

1. INTRODUCTION

In previous work [2], an improved authentication protocol for Mobile IP [5, 7] which is based on both the secret-key and the public-key cryptographic mechanism has been proposed. The protocol realizes a scalable tripartite authentication among the Mobile Host (MH), the Foreign Agent (FA) and the Home Agent (HA). Meanwhile, it improves the efficiency as compared to existing scalable protocols. In order to check the security of the protocol, we adopted the widely used BAN Logic [1] to verify the proposed authentication protocol. In the verification process, we found that the result was weaker than the other tripartite authentication schemes based on public key methods [4] or

¹CWC is a national R & D Centre funded by the Singapore National Science and Technology Board.

shared key methods [6]. However, we were able to show that the result does not compromise the security of the protocol, and furthermore, our proposed protocol is definitely more computationally efficient and scalable.

This paper is organized as follows. Section 2 presents the improved Mobile IP registration authentication protocol. Section 3 briefly presents the authentication verification logic, BAN logic. Section 4 describes the verification procedure of the proposed authentication protocol. Section 5 analyses the plausible security problem incurred because of the lack of direct MH-FA authentication. Section 6 concludes the paper.

2. IMPROVED AUTHENTICATION PROTOCOL FOR MOBILE IP

In [2], we proposed an improved authentication protocol for Mobile IP, as shown in Figure 1, which realizes the tripartite authentication among the MH, the FA and the HA. It improves the security and scalability of Mobile IP but at the same time minimizes computational overheads and re-registration delay as much as possible. In the proposal, we assume that both the MH and the HA belong to the same administrative domain, and the number of MHs an HA handles is not too large. Therefore, the symmetric key mechanism as in the standard Mobile IP can be used in the MH-HA authentication in order to take advantage of its computational efficiency and simplicity. As the MH could travel across a considerably large area, neither the HA nor the MH would know how many FAs they have to authenticate. Hence, for scalability reason, we use the public-key cryptographic mechanism for the authentication between the FA and the HA. The MH-FA pair is implicitly authenticated without compromising the security when the authentication between the MH-HA and FA-HA is successfully performed. Also, this minimizes the re-registration delay and further improves the efficiency of the protocol.

Figure 1 Tripartite two-way authentication protocol

The steps in the improved authentication protocol are explained below and Table 1 defines the terminologies used in the description.

Table 1: Definitions of the nomenclature used in the authentication protocol^a

Nomenclature	Definition
$E(X, Y)$	the encryption of Y under key X
$Auth(X)$	the message digest function value on contents X
$Priv_FA$	the private key of foreign agent
Pub_FA	the public key of foreign agent
$Priv_HA$	the private key of home agent
Pub_HA	the public key of home agent
$Sig(X, Y)$	the signature of Y with key X where $Sig(X, Y) = E(X, MD(Y))$.
$Cert_FA$	certificate of foreign agent
$Cert_HA$	certificate of home agent
Pub_CA	public key of the certification authority

^a A certificate is a data structure that binds an entity's identity to a public key with a CA's digital signature.

Step 1: When an MH detects that it is away from home, it initiates a registration procedure by sending Message #1 (Figure 2) to the FA.

Registration Request	ID	$Auth(Registration\ Request, ID, K)$
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Figure 2 Message #1 MH → FA

K is the secret key shared between the MH and the HA. ID is set as the timestamp or a nonce as described in the basic Mobile IP protocol [5] to perform replay protection. $Auth(Registration\ Request, ID, K)$ is the message digest function value on contents (Registration Request, ID, K).

Step 2: When the FA receives Message #1, it adds its certificate ($Cert_FA$) to the message, then signs it and creates Message #2 (Figure 3). Then the FA relays Message #2 to the HA. (*Note: The unshaded part is the standard Mobile IP registration message expunging the authentication extension. The shaded part contains the fields that differ from the standard protocol, including the new authentication extension.*)

Registration Request	ID	$Auth(Registration\ Request, ID, K)$	$Cert_FA$	$Sig(Priv_FA, (Registration\ Request, ID, Auth(Registration\ Request, ID, K), Cert_FA))$
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Figure 3 Message #2 FA → HA

Step 3: When the HA receives Message #2, its actions are shown in Figure 4.

Then the HA sends Message #3 (Figure 5) to the FA. It indicates whether the MH's registration is accepted or refused as well as the refusal reason. Note that, in Message #3, HA adds the FA identifier, FA_ID , into the message indicating that it trusts FA.

```

HAAction()
{
    Validate CA's signature on Cert_FA;
    if Cert_FA is invalid then return with a code indicating invalid Pub_FA;
    else Validate FA's signature with Pub_FA;
    if FA's signature is invalid then return with a code indicating invalid FA;
    else Check ID;
    if ID is invalid then return with a code indicating timeout or replay attack;
    else Check the authenticator
    if Authenticator is invalid then return with a code indicating invalid MH;
    else accepts Registration Request;
}

```

Figure 4 Actions of the HA when receives Message #2

Registration Reply	ID	FA_ID	Auth(Registration Reply, ID, FA_ID, K)	Cert_HA	Sig(Priv_HA, (Registration Reply, ID, FA_ID, Auth(Registration Reply, ID, FA_ID, K), Cert_HA))
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Figure 5 Message #3 HA → FA

Step 4: When the FA receives Message #3, its actions are shown in Figure 6.

```

FAAction()
{
    Validate CA's signature on Cert_HA;
    if Cert_HA is invalid then return with a code indicating invalid Pub_HA;
    else Validate HA's signature with Pub_HA;
    if HA's signature is invalid then return with a code indicating invalid HA;
    else Forward Message #4 to the MH;
}

```

Figure 6 Actions of the FA when receives Message #3

If HA is valid, no matter what the contents in the Registration Reply is, FA will relay the first half of Message #3, i.e., Message #4 (Figure 7).

Registration Reply	ID	FA_ID	Auth(Registration Reply, ID, FA_ID, K)
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Figure 7 Message #4 FA → MH

Step 5: When the MH receives Message #4, its actions are shown in Figure 8.

3. OUTLINE OF THE VERIFICATION METHODOLOGY BASED ON BAN LOGIC

3.1 BAN LOGIC

BAN logic [1] is a widely used logic specifically designed for analyzing the protocols for the authentication of principals in distributed computing systems.

```

MHAction()
{
    Verify the authenticator;
    if the authenticator is invalid then MH-HA authentication failed, return;
    else Check if the FA is trusted by the HA;
    if the FA is not trusted by the HA then invalid FA, return;
    else successful authentication;
}

```

Figure 8 Actions of the MH when receives Message #4

We use this logic to verify the improved authentication protocol for Mobile IP [2].

To use BAN logic for verification, one has to formalize the protocol with the BAN notations. The reason is that the conventional notations for describing an authentication protocol is not convenient for manipulation in a logic since the contents of each message often means more than necessary in the security sense. With the BAN notations, one can transform each message into a logical formula which is an idealized version of the original message. The notations shown in Table 2 will be used throughout the paper.

BAN logic uses some logical postulates to annotate an idealized protocol with assertions. An assertion usually describes beliefs held by the principals at the point in the protocol where the assertion is inserted. An annotation consists of a sequence of assertions inserted before the first statement and after each statement. To express that the statement Z follows from a conjunction of statements X and Y , we write: $\frac{X, Y}{Z}$. The postulates are listed as follows:

- The *message-meaning* rules:

For shared keys:

Rule 1: $\frac{P \models P \xleftrightarrow{K} Q, P \triangleleft \{X\}_K}{P \models Q \mid \sim X}$ (That is, if P believes that the key K is shared with Q and sees a message X encrypted under K , then P believes that Q once sent X .)

Rule 2: $\frac{P \models Q \xleftrightarrow{K} P, P \triangleleft \{X\}_Y}{P \models Q \mid \sim X}$ (That is, if P believes that the secret Y is shared with Q and sees $\{X\}_Y$, then P believes that Q once sent X .)

For public keys:

$\frac{P \models P \xleftrightarrow{K} Q, P \triangleleft \{X\}_{K^{-1}}}{P \models Q \mid \sim X}$ (That is, if P believes that the key K is the public key of Q and sees a message X encrypted under Q 's private key K^{-1} , then P believes that Q once sent X .)

- The *nonce-verification* rule:

$\frac{P \models \#(X), P \models Q \mid \sim X}{P \models Q \models X}$ (That is, if P believes that X could have been uttered only recently and that Q once sent X , then P believes that Q believes X .)

- The *jurisdiction* rule:

Table 2: Notations in BAN logic

<i>Notation</i>	<i>Definition</i>
A, B, S	specific principals
K_{ab}, K_{as}, K_{bs}	specific shared keys
K_a, K_b, K_s	specific public keys
N_a, N_b	specific statements
P, Q	general principals
X, Y	general statements
K	general encryption keys
$P \models X$	P is persuaded of the truth of X
$P \triangleleft X$	P receives a message containing X
$P \sim X$	P is known to have sent a message containing X
$P \Rightarrow X$	P has jurisdiction over X , or P is trusted as an authority on X
$\#(X)$	X has not been sent in a message belonging to a previous run of the protocol
$P \stackrel{K}{\leftrightarrow} Q$	P and Q have a <i>shared key</i> K
$\stackrel{K}{\mapsto} P$	P has K as a <i>public key</i> and K^{-1} as a <i>private key</i>
$P \stackrel{X}{\rightleftharpoons} Q$	X is a <i>secret</i> known only to P and Q
$\{X\}_K$	X is encrypted under the <i>key</i> K
$\langle X \rangle_Y$	X is <i>combined</i> with Y ; Y is a <i>secret</i> whose presence proves the identity of whoever utters $\langle X \rangle_Y$

$\frac{P \models Q \Rightarrow X, P \models Q \models X}{P \models X}$ (That is, if P believes that Q has jurisdiction over X and that P believes that Q believes X , **then** P trusts Q on the truth of X .)

The assertions are expressed in the same notations used to write messages. Moreover, annotations can be concatenated and new assertions can be derived from established ones. For example, if the X is an assertion in a legal annotation A , if X' is provable from X , and if A' is the result of substituting X' for X in A , then A' is a legal annotation.

The desired goals of an authentication protocol can be specified in BAN logic. Usually, for secret key authentication protocols, we might deem that an authentication is complete between A and B if there is a K such that:

$A \models A \stackrel{K}{\leftrightarrow} B$ (A believes that A and B has a shared key K .)

$B \models A \stackrel{K}{\leftrightarrow} B$ (B believes that A and B has a shared key K .)

Or in addition:

$A \models B \models A \stackrel{K}{\leftrightarrow} B$ (A believes that B believes that A and B has a shared key K .)

$B \models A \models A \xrightarrow{K} B$ (*B believes that A believes that A and B has a shared key K .*)

Or even weaker goals.

For public-key authentication protocols, the goal may be:

$A \models \xrightarrow{K} B$ (*A believes that B has K as a public key.*)

Or in addition: $A \models A \xrightarrow{N_a} B$ (*A believes that A and B has a secret N_a .*)

3.2 THE VERIFICATION METHODOLOGY

The verification methodology is outlined as follows:

1. Define the original authentication protocol with the conventional notations.
2. Formalize the authentication goals using BAN logic notations.
3. Derive the idealized protocol from the original one. This generally involves simplifying the protocol by omitting the parts of the message that do not contribute to the beliefs of the recipient. The idealized protocols do not include cleartext message parts because it can be easily forged.
4. Formalize the assumptions about the initial state with BAN logic notations.
5. Verify the protocol. This includes attaching the logical formulas to the statements of the protocol as assertions about the state of the system and applying the logical postulates to the assumptions and the assertions until the beliefs held by the parties in the protocol is deduced.

4. VERIFICATION OF THE IMPROVED AUTHENTICATION PROTOCOL USING BAN LOGIC

4.1 ORIGINAL PROTOCOL

The following notations are defined to be used in the verification procedure.

S: CA A: MH B: FA C: HA

X_a : Registration Request produced by A(MH)

X_c : Registration Reply produced by C(HA)

T_a : *ID_RegRequest* (*ID in Figure 2*) T_c : *ID_RegReply* (*ID in Figure 5*)

K_{ac} : the key shared between MH and HA (*K in Figure 2,3,5,7*)

K_b, K_c, K_s : the respective public keys of FA, HA and CA

$K_b^{-1}, K_c^{-1}, K_s^{-1}$: the respective private keys of FA, HA and CA

The messages in the improved authentication protocol as described in Section 2 are defined in the conventional notations as follows:

Message #1. $A \rightarrow B: \{X_a, T_a, \{X_a, T_a, K_{ac}\}_{K_{ac}}\}$

(See also Figure 2, $\{X_a, T_a, K_{ac}\}_{K_{ac}}$ corresponds to *Auth(Registration Request, ID, K)*.)

Message #2. $B \rightarrow C: \left\{ \begin{array}{l} \{X_a, T_a, \{X_a, T_a, K_{ac}\}_{K_{ac}}\}, \{B, K_b\}_{K_s^{-1}}, \\ \left\{ \{X_a, T_a, \{X_a, T_a, K_{ac}\}_{K_{ac}}\}, \{B, K_b\}_{K_s^{-1}}, \right\}_{K_b^{-1}} \end{array} \right\}$

(See also Figure 3, $\{B, K_b\}_{K_s^{-1}}$ corresponds to *Cert-FA*, the last term corresponds to FA's signature.)

Message #3. $C \rightarrow B: \left\{ \begin{array}{l} X_c, T_c, B, \{X_c, T_c, B, K_{ac}\}_{K_{ac}}, \{C, K_c\}_{K_s^{-1}}, \\ \left\{ \{X_c, T_c, \{X_a, T_c, B, K_{ac}\}_{K_{ac}}\}, \{C, K_c\}_{K_s^{-1}}, \right\}_{K_c^{-1}} \end{array} \right\}$

(See also Figure 5, $\{X_c, T_c, B, K_{ac}\}_{K_{ac}}$ corresponds to *Auth(Registration Reply, ID, FAJD, K)*, $\{C, K_c\}_{K_s^{-1}}$ corresponds to *Cert-HA*, the last term corresponds to HA's signature.)

Message #4. $B \rightarrow A: \{X_c, T_c, B, \{X_c, T_c, B, K_{ac}\}_{K_{ac}}\}$

(See also Figure 6.)

4.2 AUTHENTICATION GOALS

The goals that need to be achieved by the tripartite authentication protocol can be deduced from [1, 3, 4, 5]. Through authentication, the HA would know whether the Registration Request message it received is really produced by the MH if it can derive that the MH has the right key shared with itself and the Registration Request is freshly operated by the very key. Similarly, the MH would know whether the Registration Reply message it received is really produced by the HA if it can derive that the HA has the right key shared with itself and the Registration Reply is freshly operated by the very key. Moreover, the HA would know whether the FA is the authentic one by testing its certificate and its signature. It is the same with the FA. Finally, the MH would also know whether the FA is the authentic one and the FA would know whether the MH is a legal host. The goals are listed as follows with BAN logic notations:

- (1) $A \models C \models A \stackrel{K_{ac}}{\leftrightarrow} C$ (*A believes that C believes the shared key K_{ac} between A and C*)
- (2) $A \models C \models X_c$ (*A believes that C really sends the timely X_c*)
- (3) $C \models A \models A \stackrel{K_{ac}}{\leftrightarrow} C$ (*C believes that A believes the shared key K_{ac} between A and C*)
- (4) $C \models A \models X_a$ (*C believes that A really sends the timely X_a*)
- (5) $B \models \stackrel{K_c}{\vdash} C$ (*B believes that K_c is the public key of C*)
- (6) $B \models C \models \left\{ X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}}$ (*B believes that C really sends the timely $\left\{ X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}}$*)
- (7) $C \models \stackrel{K_b}{\vdash} B$ (*C believes that K_b is the public key of B*)

$$(8) \ C \models B \models \left\{ X_a, T_a, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}} \quad (C \text{ believes that } B \text{ really sends the timely } \left\{ X_a, T_a, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}})$$

$$(9) \ A \models B \quad (A \text{ believes the identity of } B)$$

$$(10) \ B \models A \quad (B \text{ believes the identity of } A)$$

4.3 IDEALIZED PROTOCOL

The original protocol messages are transformed into the idealized form using BAN logic notations.

Message #1. (*Cleartext, omitted*)

Message #2. $B \rightarrow C$:

$$\left\{ X_a, T_a, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}}, \{B, K_b\}_{K_s^{-1}}, \left\{ \left\{ X_a, T_a, \left\{ X_a, T_a, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}} \right\}_{\{B, K_b\}_{K_s^{-1}}} \right\}_{K_b^{-1}}$$

Message #3. $C \rightarrow B$:

$$\left\{ X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}}, \{C, K_c\}_{K_s^{-1}}, \left\{ \left\{ X_c, T_c, \left\{ X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}} \right\}_{\{C, K_c\}_{K_s^{-1}}} \right\}_{K_c^{-1}}$$

Message #4. $B \rightarrow A$: $\left\{ X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C \right\}_{K_{ac}}$

4.4 ASSUMPTIONS

We formalize the assumptions for the improved authentication protocol with BAN logic notations as in Table 3:

Table 3: Improved Authentication Protocol Assumptions

<i>A believes:</i>	<i>B believes:</i>	<i>C believes:</i>
$A \stackrel{K_{ac}}{\leftrightarrow} C$ (1)	$\stackrel{K_b}{\mapsto} B$ (2)	$\stackrel{K_c}{\mapsto} C$ (3)
$\#(T_a)$ (4)	$\#(T_a)$ (5)	$\#(T_a)$ (6)
$\#(T_c)$ (7)	$\#(T_c)$ (8)	$\#(T_c)$ (9)
	$\stackrel{K_s}{\mapsto} S$ (10)	$\stackrel{K_s}{\mapsto} S$ (11)
	$S \Rightarrow \stackrel{K_c}{\mapsto} C$ (12)	$S \Rightarrow \stackrel{K_b}{\mapsto} B$ (13)
	$S \models \stackrel{K_c}{\mapsto} C$ (14)	$S \models \stackrel{K_b}{\mapsto} B$ (15)
		$A \stackrel{K_{ac}}{\leftrightarrow} C$ (16)

4.5 VERIFICATION

According to the rule of jurisdiction, with assumption (13) and (15) listed in Table 3, we get: $\frac{C \models (S \Rightarrow^{K_b} B), C \models (S \models^{K_b} B)}{C \models^{K_b} B}$ (Accords to goal 7)

Thus, by the message meaning rule for public keys and message #2, we get:

$$\frac{C \models^{K_b} B, C \triangleleft \{ \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}} \}_{K_b^{-1}}}{C \models (B \models \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}})}$$

Thus, by the nonce verification rule and assumption (6), we get:

$$\frac{C \models \#(T_a), C \models (B \models \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}})}{C \models (B \models \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}})} \dots \dots \dots \text{(Accords to goal 8)}$$

Since message #2 contains T_a , we can derive: $C \models \#(X_a)$

By the message meaning rule (1) for shared keys and assumption (16), we get: $\frac{C \models A^{K_{ac}} C, C \triangleleft \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}}}{C \models (A \models X_a)}$

Thus, according to the nonce verification rule, we get:

$$\frac{C \models \#(X_a), C \models (A \models X_a)}{C \models (A \models X_a)} \dots \dots \dots \text{(Accords to goal 4)}$$

By the message meaning rule (1) for shared keys, with assumption (16) and message #2, we get: $\frac{C \models A^{K_{ac}} C, C \triangleleft \{ X_a, T_a, A^{K_{ac}} C \}_{K_{ac}}}{C \models (A \models A^{K_{ac}} C)}$

Since message #2 contains T_a , we can derive: $C \models \#(A^{K_{ac}} C)$

Thus, by the nonce verification rule, we get:

$$\frac{C \models \#(A^{K_{ac}} C), C \models (A \models A^{K_{ac}} C)}{C \models (A \models A^{K_{ac}} C)} \dots \dots \dots \text{(Accords to goal 3)}$$

According to assumption (12) and message #3, by the rule of jurisdiction, we get: $\frac{B \models (S \Rightarrow^{K_c} C), B \models (S \models^{K_c} C)}{B \models^{K_c} C}$ (Accords to goal 5)

Thus, by the message meaning rule for public keys and message #3, we get:

$$\frac{B \models^{K_c} C, B \triangleleft \{ \{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}}, X_c \}_{K_c^{-1}}}{B \models (C \models \{ \{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}}, X_c \})}$$

Since message #3 contains T_c , we can derive: $B \models \#(\{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}}, X_c)$

Thus, by the nonce verification rule, we get:

$$\frac{B \models \#(\{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}}), B \models (C \models \{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}})}{B \models (C \models \{ X_c, T_c, B, A^{K_{ac}} C \}_{K_{ac}})} \dots \dots \dots \text{(Accords to goal 6)}$$

By the message meaning rule for public keys, we get: $\frac{B \models^{K_c} C, B \triangleleft \{ X_c \}_{K_c^{-1}}}{B \models (C \models X_c)}$

Moreover, by the nonce verification rule, we get: $\frac{B \models \#(X_c), B \models (C \models X_c)}{B \models (C \models X_c)}$

From the content of X_c , B knows if C has refused A because of authentication failure. If not, B knows that A is trusted by C, thus we derive the new assertions:

$B \models (C \models (A \models A^{K_{ac}} C))$ (B believes that C believes that A really have the key, K_{ac} ,

shared between A and C) (Weaker than goal 10)
and then go to message #4; otherwise, B stops here.

Since message #4 contains T_c , we can derive: $A \models \#(A \stackrel{K_{ac}}{\leftrightarrow} C, X_c, B)$

By the message meaning rule (1) for shared keys and assumption (1), we get:

$$\frac{A \models A \stackrel{K_{ac}}{\leftrightarrow} C, A \triangleleft \{X_c, B\}_{K_{ac}}}{A \models (C \mid \sim \{X_c, B\})}$$

Thus, according to the nonce verification rule, we get:

$$\frac{A \models \#(X_c), A \models (C \mid \sim X_c)}{A \models (C \mid \equiv X_c)} \dots \dots \dots (\text{Accords to goal 2})$$

According to message #4 and assumption (1), by the message meaning rule (1)

for shared keys, we get: $\frac{A \models A \stackrel{K_{ac}}{\leftrightarrow} C, A \triangleleft \{X_c, T_c, B, A \stackrel{K_{ac}}{\leftrightarrow} C\}_{K_{ac}}}{A \models (C \mid \sim A \stackrel{K_{ac}}{\leftrightarrow} C)}$

Thus, according to the nonce verification rule, we get:

$$\frac{A \models \#(A \stackrel{K_{ac}}{\leftrightarrow} C), A \models (C \mid \sim A \stackrel{K_{ac}}{\leftrightarrow} C)}{A \models (C \mid \equiv A \stackrel{K_{ac}}{\leftrightarrow} C)} \dots \dots \dots (\text{Accords to goal 1})$$

Finally, by the nonce verification rule, we get:

$$\frac{A \models \#(B), A \models (C \mid \sim B)}{A \models (C \mid \equiv B)} \quad (A \text{ believes that } C \text{ believes the identity of } B) \quad . \quad (\text{Weaker than goal 9})$$

5. DISCUSSION

From the verification results above, we achieved all of the authentication goals except goals (9) and (10). That is, the results showed that the MH and HA trust each other and the FA and HA trust each other. Since the direct authentication between the MH and the FA was omitted, we could not derive that the MH and FA trust each other, but that the MH trusts that the HA trusts the FA and the FA trusts that the HA trusts the MH. However, they can be viewed as having implicitly authenticated each other. The result was weaker than the other schemes [3, 4, 6] that perform direct authentication between the MH and FA, but we will show that it is enough for a secure registration process. In other words, the weaker beliefs do not compromise the security of the protocol, which we explain as follows.

While an illegal FA, say FA_{il} , masquerades as a legal one, say FA_l , it will fail to authenticate its identity to the HA. As we know, FA_{il} does not have FA_l 's private key, so the HA will send back a Registration Reply with a code indicating that the FA failed authentication. Then the MH will try to find another FA. If FA_{il} concocts a Registration Reply and transfers it to the MH instead of the original Registration Reply, the MH will also find the truth since FA_{il} cannot concoct the right message digest which is supposed to compute with the key shared between the MH and HA. In such a case, the MH will try to find another FA. Note that, in this protocol, as long as an FA is not trusted at first, what it sends to the MH as Registration Reply will be ignored by the MH. That is, we deprived the right for the FA to refuse the MH, thus getting rid of the probability that an illegal FA performs denial-of-service attack by

issuing Registration Reply stating the MH is denied. Meanwhile, when the MH received no reply within the timeout period and it has retransmitted the Registration Reply n times (n is a predesigned number of retransmission) in vain, the MH should intelligently try to find another FA.

Likewise, while an illegal MH, say MH_{il} , masquerades as a legal one, say MH_l , it will fail to authenticate its identity to the HA because it does not have the key shared between the HA and MH_l . Hence, the FA will know it from message #3 in which contained a code indicating that the MH failed authentication, so that the FA will not trust this MH_{il} .

In summary, our protocol meets the need for a secure Mobile IP authentication, i.e., it realizes the tripartite authentication.

6. CONCLUSIONS

This paper verified and analyzed the security of an improved authentication protocol for Mobile IP, which realizes an efficient and scalable tripartite authentication among the MH, the FA and the HA. The widely used BAN logic was used in the verification process. The result of the verification showed that desired beliefs were achieved for the MH-HA pair and the HA-FA pair. However, weaker beliefs were resulted from the MH and FA pair since we omitted the direct authentication between them. However, we showed that the weakness does not compromise the security of the protocol. Therefore, the proposed improved authentication protocol meets the security requirement of Mobile IP.

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