

Cryptanalysis and improvement of a Multi-server Authentication protocol by Lu et al.

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Abstract

The increasing number of subscribers and demand of multiplicity of services has turned Multi-Server Authentication (MSA) into an integral part of remote authentication paradigm. MSA not only offers an efficient mode to register the users by engaging a trusted third party (Registration Centre), but also a cost-effective architecture for service procurement, onwards. Recently, Lu et al.'s scheme demonstrated that Mishra et al.'s scheme is unguarded to perfect forward secrecy compromise, server masquerading, and forgery attacks, and presented a better scheme. However, we discovered that Lu et al.'s scheme is still susceptible to malicious insider attack and non-compliant to perfect forward secrecy. This study presents a critical review on Lu et al.'s scheme and then proposes a secure multi-server authentication scheme. The security properties of contributed work are validated with automated Proverif tool and proved under formal security analysis.

Keywords: Multi-server authentication, remote authentication, biometrics, cryptanalysis

1. Introduction

Multi-server authentication is synonymous to overhead efficiency as it minimizes the cost whenever a client needs to access the services of multiple servers (wired and wireless) in a network. Earlier, the wired and wireless subscribers had to remember numerous passwords to procure the services of several service providers. Likewise, each service provider had to register the users and store their verifiers independently in its local repository; that procedure was inefficient for both participants. The concept is almost based upon single-sign-on where a single authentication relieves the user of multiple registrations from various servers, but with few differences. As in multi-server paradigm, the user requires to get authenticated with a server or servers each time it wants to take service out of it, using the same password and factors [1]. The authentication based on remote communication frequently involves the form of multi-server authentications that further dictates the efficiency and robustness of these techniques.

In the last decade, several multi-server authentication techniques can be seen in the literature. However, there is need to bridge more gaps in the designing of multi-server protocols. Initially, Lamport [2] gave an idea for remote authentication over an insecure network. However, the necessary condition of maintenance of a stored verifiers' database on the server's end was taken as a serious flaw due to malicious tendencies of an attacker to misuse it. Afterwards, many related authentication schemes were presented [3-5], that were exposed to many known dictionary attacks. Thereafter, numerous biometric authentication schemes are presented [6-8]. Majority of those schemes were proposed for single server environment, that puts a restriction on the number of services, a network provides. Afterwards, different smart card schemes were proposed [9-11], based on random numbers and cost efficient hash-function based schemes. Meanwhile Tsai [12] presented a multiserver authentication model. Later, Li et al. [10] found few drawbacks in [12], and came with an enhanced dynamic ID-oriented multi-server authentication model. Xue et al. [13] exposed the flaws in Li et al. and presented a new scheme. Onwards, Lu et al. found three attacks in Xue et al. i.e., off-line guessing attack, masquerading attack, and a malicious insider attack, and came with another new scheme. On the biometric side, Yang et al. and Yoon et al. [13, 17] introduced multi-server protocols. Subsequently, He [18] proved the vulnerability of both schemes for stolen card threat; insider and impersonation attack. He [18] also presented an enhanced version of protocols. Chuang et al. [20], in return proposed another smart card based biometric multiserver protocol. The scheme was confronted by Mishra et al. [21] along with the introduction of three possible attacks of DOS attack, misrepresentation and stolen card attack. Mishra et al., then proposed an anonymous authentication model with improved security features. Afterwards, He et al. [24] presented another multi-server authentication scheme. Chuang et al [31], again found forgery, masquerading, and perfect forward secrecy compromise attack in He et al, and proposed an incrementally improved robust scheme. However, the scheme is found susceptible to two threats again, i.e., lack of perfect forward secrecy, and malicious insider attack in Lu et al. [32]. The current research is based on reviewing Lu et al.'s work. Afterwards, we will present an improved scheme countering the identified threats. The security will be analyzed and performance evaluated, finally.

The section 2 defines the preliminaries including hash function, fuzzy extractor and elliptic curve essentials. Section 3 illustrates the working and review for Lu et al.'s model. The section 4 shows the proposed scheme. Section 5 demonstrates the automated security verification. While, section 6 explains the formal security analysis and section 7 demonstrates performance evaluation. The last one presents the conclusive summary.

2. Preliminaries

We describe a few preliminaries to assist the layman readers, such as, hash function, elliptic curve cryptography (ECC) and fuzzy extractor, in the following:

2.1 Hash Function

A one-sided hash function $h: \{0, 1\}^* \rightarrow Z_q^*$, should bear the following four attributes:

1. The one-sided hash function h produces a message digest of pre-determined length after getting a random string as input.
2. Given $h(\rho)=\varphi$, it is hard to take inverse $h^{-1}(\varphi)$ and recover ρ ;
3. Given ρ , it is not viable to evaluate ρ' , such that $\rho' \neq \rho$, and $h(\rho') = h(\rho)$;
4. Furthermore, it is computationally not viable to locate a pair ρ, ρ' given $\rho' \neq \rho$, and $h(\rho') = h(\rho)$.

2.2 Elliptic Curve essentials

The curve E_c could be defined as an array of multiple points over a prime field (F_q) , on a singular elliptic curve [36]:

$$t^2 \bmod q = (s^3 + ls + f) \bmod q \quad (1)$$

where $l, f, s, t \in F_q$ and $(4l^3 + 27f^2) \bmod q \neq 0$. Assuming an elliptic curve point $\mathcal{E}(s, t)$ w.r.t (1), where as, $\mathcal{F}(s, -t)$ is negative of the point \mathcal{E} . Here, we take two different points, i.e. $\mathcal{E}(s_1, t_1)$ and $\mathcal{F}(s_2, t_2)$ on (1), where as the line ln acting as tangent of (1) (subject to \mathcal{E} equals \mathcal{F}), embrace \mathcal{E} and \mathcal{F} crossing the curve (1) from $-\mathcal{G}(s_3, -t_3)$ and its reflection in relation to x-axis is $\mathcal{G}(s_3, t_3)$, that is, $\mathcal{E} + \mathcal{F} = \mathcal{G}$. The array of points constituting E_c/F_q , together with point at infinity (O), form an additive-elliptic curve cyclic group $G_q = \{(\mathcal{E}(s, t) : s, t \in F_q \text{ and } (s, t) \in E_c/F_q\} \cup \{O\}$. Moreover, an ECC-point multiplication on G_q can be represented as $\zeta \cdot \mathcal{E} = \mathcal{E} + \mathcal{E} + \dots + \mathcal{E}$ (ζ times), given the point $\mathcal{E} \in G_q$ with order ϖ , while ϖ being a positive integer and $\varpi \cdot \mathcal{E} = O$.

2.3 Fuzzy extractor

Fuzzy extractor converts the captured data (biometric stream) into randomized homogenous strings, termed as a biometric key [33-34]. These keys assist in proving the authenticity of any source generating the message. This fuzzy extractor enables the construction of a standardized pattern of random string β_i , with the noisy biometric parameter BIO_i along with a helper string γ_i . The working of fuzzy extractor is based on two key operations, i.e. *Gen* and *Rep*. The operation *Gen*, a probabilistic generation function, produces two fixed size binary strings, one is $\beta_i \in \{0, 1\}^l$ while another is helper string $\gamma_i \in \{0, 1\}^*$. The string β_i is kept secret, where as γ_i is exposed to public. To recover β_i , the deterministic reproduction operation *Rep* is utilized with input arguments containing biometric parameter BIO_i^* and helper string γ_i . For more description on fuzzy extractors, some further references [33-34] could be explored.

3. REVIEW OF LU ET AL. SCHEME

The protocol design of Lu et al.'s scheme is illustrated below:

3.1 Working of Lu et al.'s protocol

The working of Lu et al.'s scheme [32] includes registration, login & authentication sub-sections, as shown in Fig. 1. To describe the working of Lu et al.'s scheme, few notations are listed in Table 1.

Table 1. Notations description

Notations	Description
$U_i, S_j, RC:$	User (i^{th}), Server (j^{th}), Registration Centre
$ID_i, PW_i:$	Identity and password of U_i
$Gen():$	Generate fuzzy extractor
$Rep():$	Reproduce fuzzy extractor
$BIO_i:$	Biometric imprint
$x:$	U_i 's private key
$Pub/Prs:$	Public and private key of S_j
$PSK:$	Shared key between RC and S_j
$T_1-T_4:$	Timestamps
$n_1, n_2:$	Temporary session variables
$h():$	a secure hash digest function
$\oplus, //$	XOR, Concatenation

3.1.1 Initialization Phase

In this phase, the proposed model dedicates a trusted RC for registration purpose, while reserves n number of trusted servers S_j to furnish services to the users. All servers perform registraion through RC with sharing a secret PSK employing a confidential channel.

3.1.2 Registration Phase

In registration phase, the user performs registration with RC so that it may qualify for services offered through various servers. The user registraion phase incorporate the following steps:

1. The U_i sends $ID_i, h(PW_i // N_i)$ by computing and assuming a random number N_i to RC, using a confidential channel [43]. The RC receives $\{ID_i, h(PW_i // N_i)\}$, computes $R_i = h(ID_i // h(PW_i // N_i))$ and sends $\{R_i, h(PSK)\}$ to U_i by storing in smart card.
2. The U_i now computes $X_i = h(PSK) \oplus x$, and $Bi = N_i \oplus H(BIO_i)$, and stores $\{X_i, Bi\}$ also in smart card (SC). Now the SC contains the $\{R_i, X_i, Bi, h()\}$, finally.

3.1.3 Login and Authentication Phase

1. In login phase, the user uses its smart card for authenticated access to the services offered by servers. To serve the purpose, U_i inputs its ID_i, PW_i and BIO_i and computes $N_i = Bi \oplus H(BIO_i)$ and checks the equality $R_i = h(ID_i // PW_i // N_i)$. On successful verification, the

- SC allows the U_i to proceed for next procedure. Now the U_i generates n_1 , $M_1 = E_{pub}\{ID_i, n_1, h(PWi//Ni)\}$, and $M_2 = h((Xi \oplus x) // n_1 // h(PWi // Ni))$. Next, U_i sends $\{M_1, M_2\}$ towards S_j .
2. In the authentication phase the S_j receives parameters and computes $\{ID_i, n_1, h(PWi // Ni)\}$ by decrypting M_1 i.e., $D_{P_{rs}}\{M_1\}$. Then, S_j computes $h(h(PSK) // n_1 // h(PWi // Ni))$ and checks the equality $M_2 \stackrel{?}{=} h(h(PSK) // n_1 // h(PWi // Ni))$. On successful authentication it generates n_2 , then computes $M_3 = n_2 \oplus h(n_1 // ID_i // h(PWi // Ni))$, $sk_{ji} = h(n_1 // n_2 // h(PWi // Ni))$, and $M_4 = h(ID_i // n_1 // sk_{ji} // h(PWi // Ni))$. Now S_j sends the message $\{M_3, M_4\}$ to U_i .
 3. U_i receives the message and calculates $n_2 = M_3 \oplus h(n_1 // ID_i // h(PWi // Ni))$, $sk_{ij} = h(n_1 // n_2 // h(PWi // Ni))$, and checks the equality $M_4 \stackrel{?}{=} h(ID_i // n_1 // sk_{ij} // h(PWi // Ni))$. If validated, then U_i computes $M_5 = h(sk_{ij} // ID_i // n_2 // h(PWi // Ni))$, and sends the message $\{M_5\}$ to S_j .
 4. S_j receives $\{M_5\}$, and verifies the equality after computing M_5 , i.e., $M_5 \stackrel{?}{=} h(sk_{ji} // ID_i // n_2 // h(PWi // Ni))$. On successful verification, it establishes the session key $sk_{ij} = sk_{ji} = h(n_1 // n_2 // h(PWi // Ni))$ with U_i , finally.

3.2 Lu et al. scheme's cryptanalysis.

The Lu et al. scheme is found to be prone for two attacks, that is, perfect forward secrecy incompliance and malicious insider (impersonation) attack.

3.2.1 Non-compliance to perfect forward secrecy

The forward secrecy non-compliance attack may be initiated by an attacker, if the private keys of legitimate participants are revealed. This may lead to the computation of all previous session keys for a particular user U_i . If the private key ' P_{rs} ' gets leaked accidentally, the adversary may recover all previous session keys SK from intercepted messages by following the undermentioned steps.

1. After approaching the factor ' P_{rs} ', A could easily decrypt M_1 and recover $ID_i, n_1, h(PWi // Ni)$.
2. Next, the adversary can easily get n_2 from M_3 by performing $n_2 = M_3 \oplus h(n_1 // ID_i // h(PWi // Ni))$. Since, the Session key is based on n_1, n_2 and $h(PWi // Ni)$ i.e., $sk_{ij} = sk_{ji} = h(n_1 // n_2 // h(PWi // Ni))$, following this, the previous session keys can easily be constructed by using the extracted values from the stored open message parameters $\{M_1$ and $M_3\}$.

3.2.2 Malicious insider attack

The Lu et al. scheme fails to differentiate among legitimate users, already registered on valid basis, during authentication phase. A malicious legal user (insider), having the knowledge of shared key between RC and U_i , i.e., $h(PSK)$, may launch an attack easily without even stealing the smart card details. Even, a malicious insider without intercepting the message parameters $\{M_1, M_2, M_3, M_4, \text{ and } M_5\}$ may launch this attack. In Lu et al.'s protocol, S_j has no mechanism for verifying the authenticity of $h(PWi // Ni)$, or binding the identity ID_i with $h(PWi // Ni)$, given that it does not maintain any password verifier database. Neither, RC makes a use of PSK as a function in its computations during registration phase that renders the server S_j devoid of performing any positive verification. Hence, any malicious insider having the knowledge of $h(PSK)$ may launch an insider attack and easily compute M_1 and M_2 by computing $M_1 = E_{pub}\{ID_i^*, n_1^*, h(PWi^* // Ni^*)\}$ and $M_2 = h(h(PSK) // n_1^* // h(PWi^* // Ni^*))$ after generating

random values (ID_i^* , n_i^* , PW_i^* and N_i^*). The S_j authenticates U_i , only on the basis of $h(PSK)$ owned by all users in the system, which is a serious flaw in the scheme.

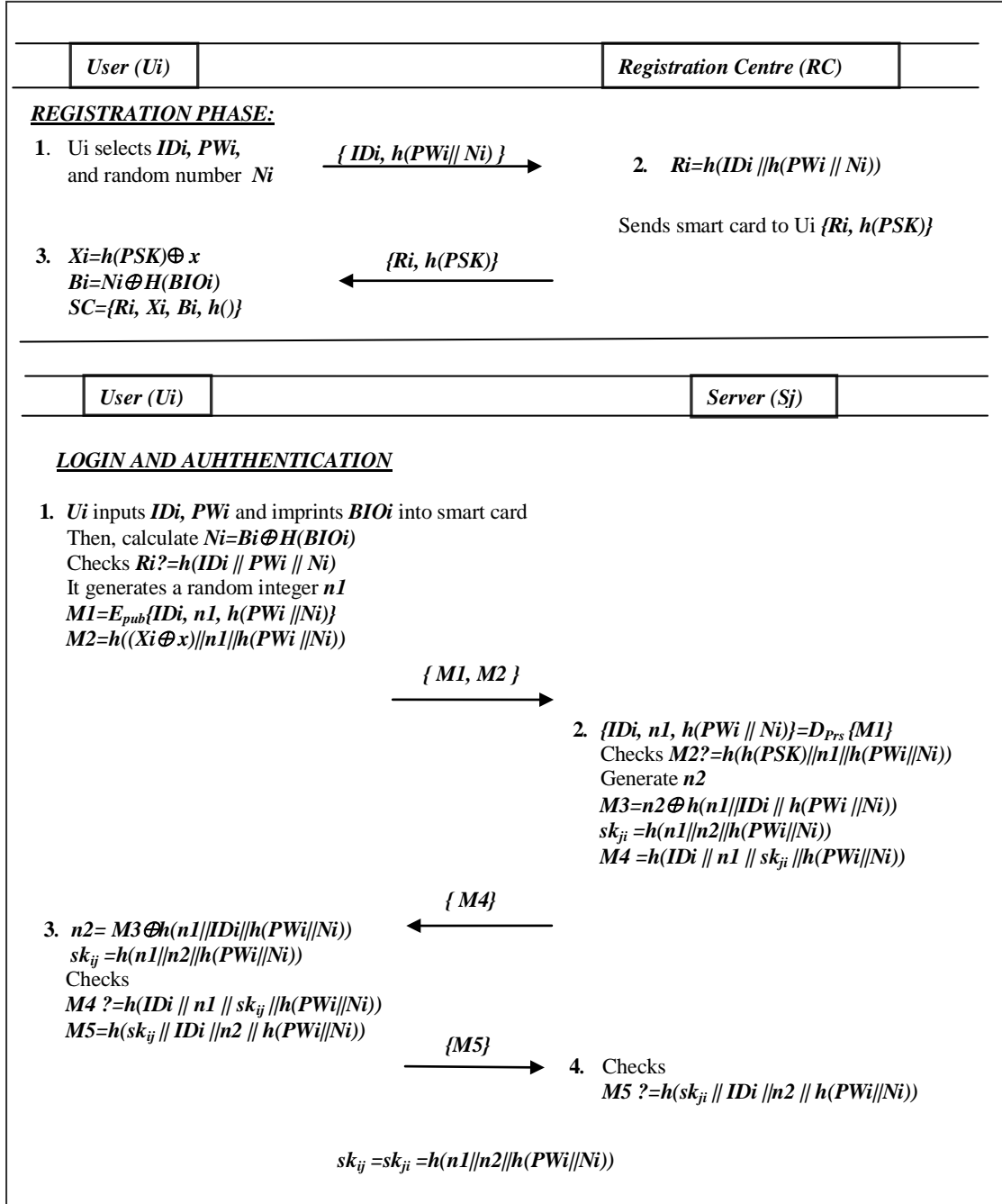


Fig. 1. Registration, login & authentication of Lu et al.'s protocol

4. PROPOSED MODEL

The discovered impersonation and forward secrecy violation attacks in Lu et al.'s scheme was the motivation for presenting an improved model. The proposed work is a smart-card based scheme that takes the user's fingerprint as biometric input into the SC to proceed with the login and authentication phase. The proposed model architecture comprises many subscribers (users), a trustworthy registration centre, and various service providers. The server S_j performs registration with RC through sharing a high entropy secret key PSK , over a confidential channel, which precedes the user registration procedure. The proposed model comprises three phases, i.e., 1) user registration phase 2) login & authentication phase (mutual authentication), and 3) password modification phase.

4.1 User Registration Phase

In this phase, U_i registers with RC by adopting the following steps:

1. The U_i generates two random numbers ω and N_i . Then, it calculates $TPWi = h(IDi \parallel h(PWi \parallel Ni))$ and $\omega \oplus TPWi$. Next, it submits IDi and $\omega \oplus TPWi$ to RC, using a secure channel.
2. The RC receives $\{IDi, \omega \oplus TPWi\}$, computes $Di = h(IDi \parallel h(PSK))$ and $Ci' = Di \oplus \omega \oplus TPWi$, and sends $\{Ci'\}$ to U_i after storing in SC.
3. Next, the user imprints biometric $BIOi$ and computes $Gen(BIOi) \rightarrow (\beta_i, \gamma_i)$. Next, it further calculates $Ri = h(IDi \parallel h(PWi \parallel Ni))$, $Bi = Ni \oplus h(\beta_i)$ and $Ci = \omega \oplus Ci'$. Next, it stores the parameters in SC which now contains $\{Ri, Ci, Bi, \gamma_i, h(\cdot)\}$, finally.

4.2 Login and authentication phase

1. In login stage, U_i inputs IDi, PWi into SC for verifying its authenticity to avail services of S_j . Next, the user imprints $BIOi$ and computes $Rep(BIOi^*, \gamma_i) \rightarrow \beta_i, Ni = Bi \oplus h(\beta_i)$. Then, it verifies the equality for $Ri \stackrel{?}{=} h(IDi \parallel h(PWi \parallel Ni))$. On successful verification, the SC allows U_i to proceed for login phase. Then, it further calculates $TPWi = h(IDi \parallel h(PWi \parallel Ni))$. Next, U_i generates a random integer n_1 , and calculates $Di = Ci \oplus TPWi$, $M_1 = E_{pub}\{IDi, n_1P, h(PWi \parallel Ni)\}$, and $M_2 = h(h(Di) \parallel n_1P \parallel h(PWi \parallel Ni) \parallel T_1)$. Finally, it sends $\{M_1, M_2, T_1\}$ to S_j .
2. In the authentication phase the S_j receives parameters and checks the equality $T_2 - T_1 > \Delta T$, ΔT being the threshold for timestamp. If the difference surpasses threshold ΔT , S_j terminates the session, otherwise computes $\{IDi, n_1P, h(PWi \parallel Ni)\}$ by decrypting M_1 i.e., $D_{prv}\{M_1\}$. Next, S_j computes $Di^* = h(IDi \parallel h(PSK))$, $M_2^* = h(Di^* \parallel n_1P \parallel h(PWi \parallel Ni) \parallel T_1)$. Now, it compares the equality $M_2^* \stackrel{?}{=} M_2$. On successful verification, it generates n_2 , and computes $M_3 = n_2P \oplus h(PWi \parallel Ni)$ and $M_4 = h(IDi \parallel n_2P \parallel h(PWi \parallel Ni) \parallel T_3)$. The S_j sends $\{M_3, M_4, T_3\}$ to U_i , and calculates the session key as $h(n_1n_2P \parallel h(PWi \parallel Ni) \parallel IDi)$, finally.
3. U_i , after receiving the message from S_j , compares timestamp against the threshold $T_4 - T_3 > \Delta T$. If this is true, aborts the session. Otherwise it constructs $n_2P = M_3 \oplus h(PWi \parallel Ni)$ and $M_4^* = h(IDi \parallel n_2P \parallel h(PWi \parallel Ni) \parallel T_3)$. Now it checks the equality for $M_4^* \stackrel{?}{=} M_4$, if the match fails, it aborts the session, otherwise constructs the session key as $h(n_1n_2P \parallel h(PWi \parallel Ni) \parallel IDi)$.

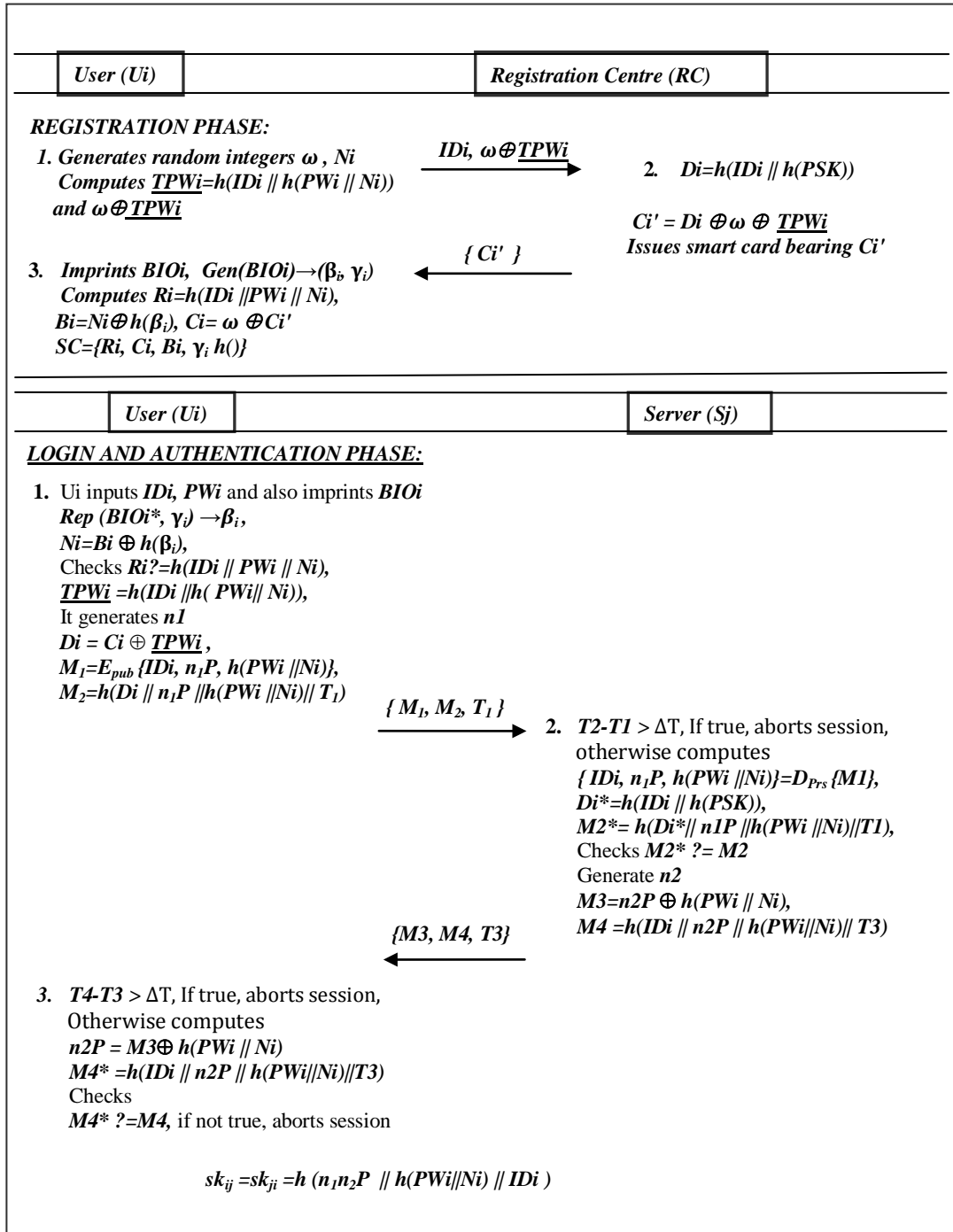


Fig. 2. Proposed Authentication Protocol

4.3 Password update phase

Ui could update its password into a novel password, i.e. PWi^{new} by initiating a procedure, which does not require any interaction with RC [14-16, 19, 22-23]. The procedure is mentioned below:

1. U_i gives as input, its identity (ID_i), password (PW_i) in SC and imprints the biometric pattern BIO_i into a device.
2. Then, SC computes $Rep(BIO_i^*, \gamma_i) \rightarrow \beta_i$ and $Ni^* = Bi \oplus h(\beta_i)$. Next, it checks whether $Ri^* \stackrel{?}{=} h(ID_i \parallel PW_i \parallel Ni^*)$ holds, if it does not hold true, the SC refuses to proceed for changing password; Otherwise, U_i inputs a new password PW_i^{new} , SC computes a new parameter $Ri^{new} = h(ID_i \parallel PW_i \parallel Ni)$ and would replace Ri with Ri^{new} to finalize the password modification.

5. Automated Tool Security Verification

The objective for security verification using an automated tool is to analyze the proposed scheme's immunity against a malicious adversary. ProVerif [41, 42] has been accepted as one of the effective tools by the research academia to test the protocols' immunity against attacks, privacy, and session key secrecy. ProVerif is based on widely accepted applied π calculus which is capable of supporting different cryptographic primitives like one-way operations, digital signatures, encryption, Diffie-Helman etc. We make a thorough analysis for measuring the efficiency and security of contributed scheme using Pro Verif simulation.

We proceed in this simulation after defining the two channels such as *SeCh*: a private channel, and *PbCh*: a public channel, among the entities RC, Sj and U_i .

```
free SeCh: channel [private].
free PbCh: channel.
```

Some variables and constants are used in the contributed model as demonstrated under:

```
const P: bitstring.
free IDi: bitstring.
free g: bitstring.
free PWi: bitstring [private].
free x: bitstring [private].
free Pub: bitstring.

free Prs: bitstring [private].
free PSK: bitstring [private].
free BIOi: bitstring [private].
```

We employed some constructors in the simulation as CONCAT, XOR, h, ECPM, ENC, and Exp are defined as concatenation, exclusive-OR, one-sided hash, elliptic curve-based scalar point multiplication, asymmetric key encryption, and exponentiation function, respectively. Here, for asymmetric decryption, we define DEC that executes decryption using a different key. Gen and Rep are the fuzzy extractor functions. Another function XOR is used for exclusive-OR, i.e. $XOR(XOR(c,d),d)=c$. The authentication primitives including constructors and destructors in this simulation are modeled for the contributed scheme as follows.

```

fun Gen(bitstring): bitstring.
fun Rep(bitstring, bitstring): bitstring.
fun h(bitstring): bitstring.
fun XOR(bitstring, bitstring):bitstring.
fun CONCAT(bitstring, bitstring):bitstring.
fun ENC(bitstring, bitstring):bitstring.
fun ECPM(bitstring, bitstring):bitstring.
fun Exp(bitstring, bitstring):bitstring.

```

```

equation forall c:bitstring,d:bitstring: XOR(XOR(c,d),d)=c.
reduc forall o: bitstring, key: bitstring: DEC(ENC(o, Pub),Prs)=o.

```

We initiate the simulation modeling by creating two events for each of the participant i.e. *Ui* and *Sj*. The events, *beginUserUi*(bitstring) and *endUserUi*(bitstring) represent start and end events for *Ui*, whereas the events, *beginServerSj*(bitstring) and *endServerSj*(bitstring) represent the same for *Sj*. The contributed scheme's authenticity may be evaluated by analyzing the corresponding link between start and end events for any participant. We describe these events as given below.

```

event beginUserUi(bitstring).
event endUserUi(bitstring).
event beginServerSj(bitstring).
event endServerSj(bitstring).

```

The three different processes are modeled, i.e. *RegistrationCentreRC*, *UserUi*, and *ServerSj* against *RC*, *Ui* and *Sj*, respectively. First, the *UserUi* process forwards the parameters *IDi*, *PWi*' on confidential channel *SeCh* to *ServerSj* process. Next, after getting *xCi*, *UserUi* further calculates *Ri* and *Bi*. In mutual authentication phase, *UserUi* compares *Ri* and *Ri'* after calculating *Ri'*. It further computes *PWi''* and *Di*, which are used in the construction of *M1* and *M2*. The *UserUi* then submits the message (*M1*, *M2*, *T1*) to *ServerSj* using the open channel *PbCh*. Finally, the *UserUi*, after receiving the message (*M3*, *M4*, *T3*) from *SeverSj*, computes *n2P'*, *M4'* and compares *xCM4'* with *M4'* and validates the *ServerSj* process, otherwise, aborts the session. Then it proceeds for calculating the session key *SK*.

```

let UserUi=
new Ni:bitstring;
new w:bitstring;
let Pub=Exp(g,Prs) in
let PWi' = h(CONCAT(IDi,h(CONCAT(PWi,Ni)))) in
let W= XOR(w, PWi') in

```

```

out (SeCh,(IDi, W));
in(SCh,(xCi*:bitstring));
let (u: bitstring, v: bitstring) = Gen(BIOi) in
let Ri = h(CONCAT(IDi, (PWi, Ni))) in
let Ci= XOR(w, xCi*) in
let Bi= XOR(Ni, h(u)) in
event beginUserUi(IDi):
new BIOi*: bitstring;
let u* = Rep(BIOi*, v) in
let Ni'= XOR(Bi, h(u*)) in
let Ri' = h(CONCAT(IDi, (PWi, Ni'))) in
if (Ri = Ri') then
let PWi'' = h(CONCAT(IDi, h(CONCAT(PWi, Ni')))) in
new n1:bitstring;
let Di = XOR(xCi, PWi'') in
let M1 = ENC(CONCAT(IDi, (ECPM(n1, P), h(CONCAT(PWi, Ni')), Di)), Pub) in
new T1:bitstring;
let M2 = h(CONCAT(h(Di), (ECPM(n1, P), h(CONCAT(PWi, Ni')), T1))) in
out(PbCh, (M1, M2, T1));
in(PbCh, (xM3:bitstring, xM4:bitstring, xT3:bitstring));
let n2P' = XOR(xM3, h(CONCAT(PWi, Ni'))) in
let M4' = h(CONCAT(IDi, (n2P', h(CONCAT(PWi, Ni')), xT3))) in
if(xM4 = M4') then
let SK = h(CONCAT(ECPM(n1, n2P'), (h(CONCAT(PWi, Ni')), IDi))) in
event endUserUi(IDi)
else
0.

```

The process *RegistrationCentreRC* gets xID_i and xPW_i' parameters from *UserUi* using a confidential channel *SeCh*, and calculates Di and $Ci = XOR(Di, xPW_i')$. Finally, it sends Ci towards *UserUi* process using *SeCh*.

```

let RegistrationCentreRC=
in (SeCh,(xIDi:bitstring, xW:bitstring));
let Di = h(CONCAT(xIDi, h(PSK))) in
let Ci* = XOR(Di, xW) in
out(SeCh, (Ci*));
0.

```

The *ServerSj* process receives the parameters xM_1 , xM_2 and xT_1 from *UserUi* process for verifying authenticity. Next, it decrypts xM_1 using its private key (Prs), and recovers $\langle xID_i, xN_1P, xhPN, xDi \rangle$ tuple. Next, it computes Di' , M_2' and compares xM_2 against M_2' . If found true, then it validates the *UserUi* process, otherwise aborts the session. Following the positive verification of *UserUi* process, it further computes M_3 by doing $XOR(ECPM(n_2, P), h(xhPN))$ and M_4 . Then this process sends the message (M_3, M_4, T_3) towards *UserUi* using a public channel. Then the *UserUi* process verifies the authenticity of received message, finally.

```

let ServerSj=
event beginServerSj(Pub):
in(PbCh,(xM1:bitstring,xM2:bitstring,xT1:bitstring)):
let (xIDi:bitstring,xn1P:bitstring,xhPN:bitstring,xDi:bitstring)=DEC(xM1,Prs) in
let Di' = h(CONCAT(xIDi,h(PSK))) in
new T2:bitstring;
let M2' = h(CONCAT(h(Di'),(xn1P,xhPN,T2))) in
if (xM2 = M2') then
new n2:bitstring;
let M3 = XOR(ECPM(n2,P),h(xhPN)) in
new T3:bitstring;
let M4 = h(CONCAT(IDi,(ECPM(n2,P),xhPN,T3))) in
out(PbCh,(M3,M4,T3));
event endServerSj(Pub)
else
0.

```

The three principals get agreed to an unrestricted number of sessions in parallel, for these processes will be in replication as depicted below.

```

process
((!UserUi) | (!RegistrationCentreRC) | (!ServerSj) )

```

We define the following queries to test the security and correctness of the proposed protocol.

```

free SK:bitstring [private].
query attacker(SK).
query id:bitstring; inj-event(endUserUi(id)) ==> inj-event(beginUserUi(id)) .
query id:bitstring; inj-event(endServerSj(id)) ==> inj-event(beginServerSj(id)) .

```

The following results are the outcome of implementing above queries in this simulation.

```

RESULT inj-event(endServerSj(id)) ==> inj-event(beginServerSj(id)) is true.
RESULT inj-event(endUserUi(id_1580)) ==> inj-event(beginUserUi(id_1580)) is true.
RESULT not attacker(SK[]) is true.

```

The first two results clearly identity that these processes begin and also end successfully, whereas the third outcome suggests that the attacker-based query is unable to output the session key as constructed among the processes during mutual authentication procedure.

6. SECURITY ANALYSIS

This section demonstrates security analysis of contributed scheme in the follow up of discovered threats in Lu et al.'s protocol. This analysis depicts that the proposed work is resistant to all of the threats as listed in [Table 2](#), particularly malicious insider attack and perfect forward secrecy compromise as posed to Lu et al. scheme. The [Table 2](#) and III list the functionality comparison and the computational cost of different schemes. Before delving into

an informal security analysis, first, we define few terms [36] as used in the analysis.

Definition 1

An Elliptic Curve Computational Diffie–Hellman problem (ECCDHP) is acknowledged as: Given σ G 's generator $P \in E_q$, $\sigma P, \mu P \in E_q$, it is infeasible to compute $\sigma\mu P \in E_q$ without having the knowledge of $\sigma \in Z_P^$ or $\mu \in Z_P^*$.*

Definition 2

The Elliptic Curve Discrete Logarithm Problem (ECDLP) is acknowledged as: Given a point $\Theta = \sigma P$ on Elliptic Curve, it is intractable to figure out the scalar σ , given $\Theta \in E_q$ and $P \in E_q$.

The informal security analysis of the contributed model is elaborated as follows:

Proposition 1. *The proposed scheme thwarts replay attack.*

In replay attacks, the attacker replays the intercepted messages at any time to misrepresent the legitimate entities.

Proof. An adversary \mathcal{A} having the intercepted contents $\{M_1, M_2, T_1, M_3, M_4, T_3\}$ may attempt to replay the parameters to betray the legitimate participants. Nonetheless, the use of T_1 and T_3 timestamps by either of the participants debars an adversary to launch such attack. Since, if \mathcal{A} will employ the same timestamp for generating a fake login request, it fails the threshold. On the other hand if adversary generates its own message with a new timestamp, it fails the equality check $M_2^* \neq M_2$, subsequently. Hence, this fact proves the above proposition that proposed scheme can successfully thwart a replay attack.

Proposition 2. *The contributed protocol is resistant to Man-in-the-Middle attack.*

In this threat, a silent intermediary manipulates the communication on both ends by replaying or constructing messages. In this attack, the legal participants believe erroneously that these are talking to an intended recipient.

Proof. In contributed scheme, the adversary is not able to initiate MiTM attack, since none of the intermediaries could approach the parameters included in a message i.e., $ID_i, h(PW_i || N_i)$, and D_i , using a public channel. Hence, it may not be able to construct the original message $M_1 = E_{pub}\{ID_i, n_1P, h(PW_i || N_i)\}$, and $M_2 = h(D_i || n_1P || h(PW_i || N_i) || T_1)$ with a fresh timestamp, that makes the server believe that \mathcal{A} is a legitimate entity.

Proposition 3. *Our scheme prevents modification threat.*

The modification attacks could be initiated by an attacker if it resends the message after reconstructing it in an unauthorized manner towards a legal entity.

Proof. If any adversary tries to modify the intercepted messages $\{M_1, M_2, T_1, M_3, M_4, T_3\}$, it may not change the messages M_1 – M_4 except T_1 and T_3 parameters. However, an adversary may not be able to perform any timestamp based update in M_1 – M_4 messages, since the adversary's modification might be successful in passing the timestamp threshold check ΔT , nevertheless, it may not be able to pass the $M_2^* \neq M_2$ and $M_4^* \neq M_4$ checks. Hence, it proves the proposition that the proposed scheme prevents modification attacks.

Proposition 4. *The contributed work is resistant to password-guessing attack.*

Proof. The offline-password guessing attack [26-30] may be tried when an attacker attempts to extract or compute U_i 's password by employing the intercepted messages $\{M_2, M_4\}$ or stolen smart card information i.e. $\{R_i, C_i, B_i\}$. However, adversary may not be able to guess PW_i from $M_2 = h(D_i || n_1P || h(PW_i || Ni) || T_1)$ or $M_4 = h(ID_i || n_2P || h(PW_i || Ni) || T_3)$, by the reason of not having access to D_i, n_1P, ID_i, Ni and n_2P parameters. At the same time, password computation or dictionary guessing attack, from $R_i = h(ID_i || h(PW_i || Ni))$, $C_i = D_i \oplus TPW_i$ or $B_i = Ni \oplus h(\beta_i)$ is not possible until Ni and ID_i factors are known. Where, Ni can only be extracted with the imprinted biometric BIO_i and extracted parameter β_i , while an access to the latter is definitely an unfeasible task. Hence, the above proposition is proved.

Proposition 5. *The contributed work is immune to stolen-verifier attack.*

Proof. An attacker might steal secret information stored on a server's repository and exploit it for some malicious purpose, however, only if the server maintains the repository of users' verifiers and shared secrets. While, the contributed protocol foregoes the maintenance of any kind of database on server's or RC's end, which makes the proposed scheme naturally immune to stolen-verifier attack. Hence, this fact sustains the above proposition.

Proposition 6. *The proposed scheme foils the offline dictionary attack, in case the user's smart card gets stolen.*

In offline dictionary threat, the adversary after stealing SC, attempts to utilize the extracted contents for guessing low-entropy secrets by inputting all possible combinations from the dictionary.

Proof. An adversary after making away with the stolen contents of smart card, may attempt to use for some malicious purpose. Nevertheless, those contents including R_i, C_i, B_i serve to be useless, given that PW_i recovery or dictionary guessing attack, from $R_i = h(ID_i || PW_i || Ni)$ is not possible until the parameters Ni and ID_i are recovered. Ni can neither be extracted until the parameters β_i and n_2P are accessed. Likewise, C_i is also a function based on XOR i.e., $C_i = D_i \oplus TPW_i$. The PW_i cannot be guessed out of C_i or TPW_i in any manner, by the adversary. Thus, this proof upholds the above proposition.

Proposition 7. *The contributed scheme achieves session-key security.*

This security feature affirms that the established session key is known merely to the authorized participants, i.e., U_i and server.

Proof. In contributed model, the constructed session key is based on $SK = h(n_1n_2P || h(PW_i || Ni) || ID_i)$. To construct a legal session key, the attacker has to access n_1, n_2, ID_i and $h(PW_i || Ni)$. An adversary cannot derive n_1 from n_1P , neither n_1P from M_1 , which is encrypted using the public of S_j . At the same time, it also needs ID_i and $h(PW_i || Ni)$ to create a valid session key. Hence, the above proposition is proved.

Proposition 8. *The contributed protocol maintains the attribute of known-key security.*

The known-key security feature points to the inability of guessing private keys of the associated participants, subject to the compromised session key.

Proof. If we assume, the session key $SK = h(n_1n_2P \parallel h(PWi \parallel Ni) \parallel IDi)$ gets compromised by attacker, yet it may not be able to guess the secret keys of legal participants. The server private key Prs is quite safe, since the Ui makes a use of its public key for encryption, and Sj uses this Prs for decryption. Likewise, the Ui 's password PWi cannot be guessed until Ni , IDi and n_1n_2P are not known to the adversary. Hence, for the known-key security, the above proposition is proved.

Proposition 9. *The contributed scheme stands compliant to perfect forward secrecy.*

This security feature affirms the security of past session keys, in case the participants' long-term secrets are exposed.

Proof. The contributed work provides perfect forward secrecy, in case the private keys of one or more participants gets exposed, since, the contributed work employs ECC operations to ensure the ECDLP property that in turn leads to forward secrecy. In case, the adversary gets the participants' (Server/RC/User) secrets such as Prs , PSK , and PWi of server, yet A is not able to compute the previous session keys for hardness of computing either n_1 out of n_1P , or n_2 from n_2P due to ECDLP and ECCDHP. Hence, the proposition is proved.

Proposition 10. *The proposed scheme mutually authenticates the intended participants.*

This feature stipulates that the parties involved should verify one another in the same protocol.

Proof. The contributed work affirms mutual authentication to involved participants as also proved in section 7 (BAN logic). The Sj starts authenticating Ui on the basis of received message $\{M_1, M_2, T_1\}$. Then it decrypts M_1 i.e., $\{IDi, n_1P, h(PWi \parallel Ni)\} = D_{Prs} \{M_1\}$, computes $Di^* = h(IDi \parallel h(PSK))$, and $M_2^* = h(Di^* \parallel n_1P \parallel h(PWi \parallel Ni) \parallel T_1)$. Finally, Sj compares $M_2^* ? = M_2$, and authenticates on successful equality check. Otherwise, aborts the session. Likewise, Ui authenticates Sj on the basis of received message $\{M_3, M_4, T_3\}$. Ui extracts n_2P from M_3 by $n_2P = M_3 \oplus h(PWi \parallel Ni)$, and then computes $M_4^* = h(IDi \parallel n_2P \parallel h(PWi \parallel Ni) \parallel T_3)$. Finally it compares the equality check $M_4^* ? = M_4$, if true, authentication with Sj is validated. Otherwise, aborts the session.

Proposition 11. *The contributed work stipulates the user's anonymity and privacy.*

An anonymous authentication protocol should not mitigate the server's chances of verifying the user's authenticity. After the exchange of messages on an insecure channel during login and authentication phase, and successful session key establishment onwards, an attacker won't be able to discern about the identities of involved participants by examining the intercepted messages [43].

Proof. In proposed model, the user submits its identity IDi in message $\{M_3\}$ by encrypting through Sj 's public key. This prevents any possibility of Ui 's leakage of identity which substantiates the proposition.

Proposition 12. *The contributed work provides defense against previlged insider attack.*

The previlged insider attack could be initiated if a malicious adversary (priveleged insider on the registration authority's end) gets access to communicated parameters during registration process, and further launch impersonation attack and session key guessing attacks.

Proof. In proposed model, if a previlged malicious insider gets access to ID_i and $\omega \oplus TPW_i$ parameters, it cannot guess either password from $\omega \oplus TPW_i$ or initiate any kind of impersonation attack. Moreover, in case, the adversary gets the smart card contents, it cannot compute Di from Ci on the basis of pre-stolen $\omega \oplus TPW_i$ during registration processs. Since, Di is the basis of mutual authentication between the participants, the inaccessibility of Di to adversary debars it to lauch any kind of impersonation attack. Therefore, our scheme provide resistance to previlged insider attack, proving the above proposition.

Now we present the security evaluation related to contributed work using Burrows-Abadi-Needham logic (BAN) logic [25]. This logic based model enables us to analyze authentication protocols in terms of session key generation in a secure manner, and mutual authentication between the intended participants.

In this logical analysis, principals (\mathcal{A} and \mathcal{V}) refer to generic instances or agents, participating in a protocol. Some related notations w.r.t logical analysis are given as follows:

$\mathcal{A} \models M$: \mathcal{A} believes the statement M .

$\mathcal{A} \triangleleft M$: \mathcal{A} sees M . \mathcal{A} receives the message M and reads or may put it to any use.

$\mathcal{A} \mid \sim M$: \mathcal{A} once said M . Some time ago, \mathcal{A} had sent some message M after generating it.

$\mathcal{A} \Rightarrow M$: \mathcal{A} enjoys jurisdiction over M ; or \mathcal{A} can influence M and be trusted.

$\#(M)$: The message M is fresh and not replayed.

$\langle M \rangle_3$: The formulae M is used in combination with formulae 3 .

$(M, 3)$: M or 3 being the part of message $(M, 3)$.

$\{M, 3\}_s$: M or 3 is encrypted using symmetry key s .

$\langle M, 3 \rangle_s \mapsto \mathcal{A}$: M or 3 is encrypted using public key s of \mathcal{A} .

$(M, 3)_s$: M or 3 is hashed using the key s .

$\mathcal{A} \xleftrightarrow{s} \mathcal{V}$: \mathcal{A} and \mathcal{V} can securely contact using shared key s .

The assumptions or postulates related to current analysis are illustrated below:

$$R1. \text{ Message meaning rule: } \frac{\mathcal{A} \mid \equiv \mathcal{A} \xleftrightarrow{s} \mathcal{V}, \mathcal{A} \triangleleft \langle M \rangle_3}{\mathcal{A} \mid \equiv \mathcal{V} \mid \sim M}$$

$$R2. \text{ Nonce verification rule: } \frac{\mathcal{A} \mid \equiv \#(M), \mathcal{A} \mid \equiv \mathcal{V} \mid \sim M}{\mathcal{A} \mid \equiv \mathcal{V} \mid \equiv M}$$

$$R3. \text{ Jurisdiction rule: } \frac{\mathcal{A} \mid \equiv \mathcal{V} \Rightarrow M, \mathcal{A} \mid \equiv \mathcal{V} \mid \equiv M}{\mathcal{A} \mid \equiv M}$$

$$R4. \text{ Freshness conjuncatenation rule: } \frac{\mathcal{A} \mid \equiv \#(M)}{\mathcal{A} \mid \equiv \#(M, 3)}$$

$$R5. \text{ Belief rule: } \frac{\mathcal{A}|\equiv(M), \mathcal{A}|\equiv(\exists)}{\mathcal{A}|\equiv(M, \exists)}$$

$$R6. \text{ Session key rule: } \frac{\mathcal{A}|\equiv \boxtimes (M), \mathcal{A}|\equiv \forall |\equiv M}{\mathcal{A}|\equiv \mathcal{A} \longleftrightarrow \forall}$$

$$R7. \text{ Public key encryption rule: } \frac{\mathcal{A}|\equiv \mathcal{A} \mapsto \forall, \mathcal{A} \triangleleft \{M\}_{\mathcal{A}^{-1}}}{\mathcal{A}|\equiv \forall \sim M}$$

Our proposed scheme needs to follow these goals for proving its session key-based security using BAN logic, keeping in view the above assumptions.

$$\begin{aligned} \text{Goal1 : } & \text{Sj} \mid \equiv \text{Ui} \xleftrightarrow{SK} \text{Sj} \\ \text{Goal2 : } & \text{Sj} \mid \equiv \text{Ui} \mid \equiv \text{Ui} \xleftrightarrow{SK} \text{Sj} \\ \text{Goal3 : } & \text{Ui} \mid \equiv \text{Ui} \xleftrightarrow{SK} \text{Sj} \\ \text{Goal4 : } & \text{Ui} \mid \equiv \text{Sj} \mid \equiv \text{Ui} \xleftrightarrow{SK} \text{Sj} \end{aligned}$$

The generic protocol can be described as:

$$\begin{aligned} m_1: & \text{Ui} \rightarrow \text{Sj}: M_1, M_2, T_1 \\ m_2: & \text{Sj} \rightarrow \text{Ui}: M_3, M_4, T_3 \end{aligned}$$

We adapt the generic protocol into idealized form as given below.

$$\begin{aligned} m_1: & \text{Ui} \rightarrow \text{Sj}: \langle IDi, n_1P, h(PWi \parallel Ni), Di \rangle_{Pub} \mapsto \text{Sj}, \langle n_1P, h(PWi \parallel Ni), T_1 \rangle_{Di}, T_1 \\ m_2: & \text{Sj} \rightarrow \text{Ui}: \langle n_2P \rangle_{h(PWi \parallel Ni)}, \langle IDi, n_2P, T_3 \rangle_{h(PWi \parallel Ni)}, T_3 \end{aligned}$$

Secondly, the undermentioned premises are set up for proving the robustness of our scheme.

$$\begin{aligned} P1 : & \text{Ui} \mid \equiv \# n_1, T_1 \\ P2 : & \text{Sj} \mid \equiv \# n_2, T_3 \\ P3 : & \text{Ui} \mid \equiv \text{Sj} \xleftrightarrow{Di} \text{Ui} \\ P4 : & \text{Sj} \mid \equiv \text{Sj} \xleftrightarrow{Di} \text{Ui} \\ P5 : & \text{Ui} \mid \equiv \text{Sj} \Rightarrow n_2P \\ P6 : & \text{Sj} \mid \equiv \text{Ui} \Rightarrow n_1P \end{aligned}$$

By using the above notations, rules, premises and idealizations, we get to the following proofs and derivations:

Mutual Authentication accuracy:

For verifying mutual authentication between Ui and Sj, we visualize the messages m1 and m2, stating the idealized form:

$$\begin{aligned} m_1: & \text{Ui} \rightarrow \text{Sj}: \langle IDi, n_1P, h(PWi \parallel Ni), Di \rangle_{Pub} \mapsto \text{Sj}, \langle n_1P, h(PWi \parallel Ni), T_1 \rangle_{Di}, T_1 \\ m_2: & \text{Sj} \rightarrow \text{Ui}: \langle n_2P \rangle_{h(PWi \parallel Ni)}, \langle IDi, n_2P, T_3 \rangle_{h(PWi \parallel Ni)}, T_3 \end{aligned}$$

Lemma 1: *Sj can correctly prove the authenticity of login request message from Ui.*

Proof. User Ui generates the message (M_1, M_2, T_1) and sends towards server Sj in order to login it and avail its services. Sj gets timestamp along with some other session based parameters and verify the correctness for the source of the message as follows.

We apply the seeing rule, and get the derivation

$$D1: Sj \triangleleft \langle IDi, n_1P, h(PWi // Ni), Di \rangle_{Pub} \mapsto Sj, \langle n_1P, h(PWi // Ni), T_1 \rangle_{Di}, T_1$$

Applying D1, P4 and R1,

$$D2: Sj \models Ui \sim n_1P, T_1$$

According to P1, P6, and R4

$$D3: Sj \models \#(n_1P, T_1)_{Di}$$

According to D2, D3 and R2, we have

$$D4: Sj \models Ui \models (n_1P, T_1)_{Di}$$

According to P4, D4 and the application of R3, we can say

$$D5: Sj \models n_1P, T_1$$

Hence, after verifying the timestamp freshness, Sj proves the accuracy of message source.

Lemma 2: *Ui can appropriately prove the authenticity of response message from Sj.*

Proof. In our protocol, the server Sj generates the message (M_3, M_4, T_3) and sends to Ui along with timestamp, in response to its Ui's login request. Ui proves the authenticity of Sj by checking the parameters freshness as follows.

By applying seeing rule, we get to this derivation,

$$D6: Ui \triangleleft \langle n_2P \rangle_{h(PWi // Ni)}, \langle IDi, n_2P, T_3 \rangle_{h(PWi // Ni)}, T_3$$

According to D6, P3 and R1,

$$D7: Ui \models Sj \sim n_2P, T_3$$

According to P2, P5, and R4

$$D8: Ui \models \#(n_2P, T_3)_{Di}$$

According to D7, D8 and R2, we have

$$D9: Ui \models Sj \models (n_2P, T_3)_{Di}$$

According to P3, D9 and the application of R3, we can say

$$D10: Ui \models n_2P, T_3$$

Hence, after verifying the timestamp freshness, Ui proves the accuracy of message source.

Theorem 1.

Proof. In relation to Lemma 1, the S_j may correctly prove the authenticity of a login request from user. In relation to Lemma 2, the user U_i may also correctly prove the authenticity of the response message from the server. Hence, we may deduce that U_i and S_j mutually authenticate one another.

Session Key Agreement:

A single session key, $Sk = h(n_1n_2P \parallel h(PWi \parallel Ni) \parallel ID_i)$, can be established and agreed upon between the communicating entities in proposed protocol. While, $(ID_i, n_1n_2P, h(PWi \parallel Ni))$ are necessary parameters for session key generation. This session key agreement between the participants can be achieved as follows.

According to P2, D4, and R2, we get

$$D11: S_j \models U_i \xrightarrow{SK} U_i \quad (\text{Goal 2})$$

According to P2, D11, and R6

$$D12: S_j \models S_j \xrightarrow{SK} U_i \quad (\text{Goal 1})$$

According to P1, D9, and R2, we get

$$D13: U_i \models S_j \xrightarrow{SK} U_i \quad (\text{Goal 4})$$

According to P1, D13, and R6

$$D6: U_i \models S_j \xrightarrow{SK} U_i \quad (\text{Goal 3})$$

Hence, the above analysis (BAN) sufficiently verifies that the contributed protocol can achieve mutual authenticity, while the established session key SK is mutually agreed between the legal participants (U_i and S_j).

Formal Security Analysis

We conduct a formal analysis with random oracle model, that validates the argument in the favor of a secure model [37-40]. For this purpose, we can define the hash function $h(.)$ as follows.

Definition 3 We define a one-sided function, hash as $h_f: \{0, 1\}^* \rightarrow \{0, 1\}^\ell$, that generates a binary string of length ℓ i.e. $h_f(y) = \{0, 1\}^\ell$ as output, on providing a randomly sized binary string $y \in \{0, 1\}^\ell$ as input.

We define the following two oracles that could be used by an adversary \mathcal{A} , and outputs unconditionally as following:

reveal1: This oracle produces δ out of the corresponding hash value $\vartheta = h_f(\delta)$, unconditionally.

reveal2: The *reveal2* oracle outputs scalar k from public key $\mathcal{Q} = kP$, unconditionally, given $P \in E_q(a, b)$.

Algorithm 1. $EXP1_{PSBASME}^{HASH}$

1. Eavesdrop the Login request message $\{M_1, M_2, T_1\}$ in the login phase, where $M_1 = E_{pub}\{IDi, n_1P, h_f(PWi || Ni)\}$ and $M_2 = h_f(Di || n_1P || h_f(PWi || Ni) || T_1)$
2. Call Reveal oracle on the input M_2 to produce $Di', n_1P, h(PWi || Ni)', T_1'$ as $(Di || n_1P || h_f(PWi || Ni) || T_1') \leftarrow reveal1(M_2)$
3. Call Reveal oracle on the input Di' to produce $IDi', h_f(PSK)$ as $(IDi' || h_f(PSK)) \leftarrow reveal1(Di')$
4. **If** $(T_1' = T_1)$ **Then**
5. Eavesdrop the Login request message $\{M_3, M_4, T_3\}$ in the authentication phase, where
 $M_3 = n_2P \oplus h_f(PWi || Ni)$ and $M_4 = h_f(IDi || n_2P || h_f(PWi || Ni) || T_3)$
6. Call Reveal oracle on input M_4 to retrieve $IDi, n_2P', h_f(PWi || Ni)'', T_3'$ as $h_f(IDi || n_2P || h_f(PWi || Ni) || T_3') \leftarrow reveal1(M_4)$
7. **If** $(T_3' = T_3)$ and $(h_f(PWi || Ni)' = h_f(PWi || Ni)'')$ **Then**
8. Compute $n_2P^* = h_f(PWi || Ni)' \oplus M_3$
9. **If** $(n_2P^* = n_2P')$ and $(IDi' = ID)$ **Then**
10. Accept IDi as the true identity of user, and PSK as the valid shared secret between RC and Sj.
11. Return 1 (True)
12. Else
13. Return 0 (False)
14. End if
15. **End if**

Theorem2

By undertaking ECDLP assumption, given that one-sided hash function performs narrower to a random oracle, the contributed technique stands protected against attacker \mathcal{A} , if \mathcal{A} tries to derive the identity (IDi) of some user (Ui) and shared secret PSK between RC and Sj.

Proof.

Here, we plan to set an attacker \mathcal{A} , capable of deriving the Ui 's original IDi and shared secret PSK between RC and Sj, by employing random oracles $Reveal1$, $Reveal2$ and running the experiment as shown in algorithm $EXP1_{PSBASME}^{HASH}$. The success probability regarding $EXP1_{PSBASME}^{HASH}$ is $Sucss1 = \text{Pro.2}[EXP1_{PSBASME}^{HASH} = 1] - 1$, while $\text{Pro}[E_v]$ characterize the probability of an event E_v . The gain function for the current experiment turns out to be $Adv_{PSBASME}^{HASH}(t_{m1}, q_{Ry1}, q_{Ry2}) = \max_{\mathcal{A}} [Sucss1_{PSBASME}^{HASH}]$, having execution time t_{m1} while the Reveal-queries q_{Ry1} and q_{Ry2} maximized on attacker (\mathcal{A}). We term our contributed technique to be protected of \mathcal{A} for deriving IDi , PSK , if $Adv_{PSBASME}^{HASH}(t_{m1}, q_{Ry1}, q_{Ry2}) \leq \alpha$ for adequately small $\alpha > 0$. In accordance to the current experiment, if \mathcal{A} could invert a one-sided hash function $h(\cdot)$, then solving the hard problem ECDLP, onwards it could comfortably recover the valid IDi and shared secret PSK among the participants, and finally wins this game. Nonetheless, in keeping with definition (2), this would not be computationally viable to reverse the related hash-based function, the reason being $Adv_{PSBASME}^{HASH}(t_{m1}) \leq \alpha$ for adequately small $\alpha > 0$.

Algorithm 2 $EXP2_{PSBASME}^{HASH,SC}$

1. Eavesdrop the Login request message $\{ M_1, M_2, T_1 \}$, where $M_1 = E_{pub}\{IDi, n_1P, h_f(PWi || Ni)\}$ and $M_2 = h_f(h_f(Di) || n_1P || h_f(PWi || Ni) || T_1)$
2. Call the oracle for input M_2 to produce $Di', n_1P, h_f(PWi || Ni)', T_1'$ as $(Di || n_1P || h_f(PWi || Ni) || T_1) \leftarrow reveal1(M_2)$
3. Call the oracle for input n_1P to produce n_1' as $n_1' \leftarrow reveal2(n_1P)$
4. Call the oracle for input Di' to produce $IDi', h_f(PSK)$ as $(IDi' || h_f(PSK)) \leftarrow reveal1(Di')$
5. **If** $(T_1' = T_1)$ **Then**
6. Eavesdrop the Login request message $\{M_3, M_4, T_3\}$ in the authentication phase, where
 $M_3 = n_2P \oplus h_f(PWi || Ni)$ and $M_4 = h_f(IDi || n_2P || h_f(PWi || Ni) || T_3)$
7. Call Reveal oracle on input M_4 to produce $IDi, n_2P, h_f(PWi || Ni)'', T_3'$ as $h_f(IDi || n_2P || h_f(PWi || Ni) || T_3) \leftarrow reveal1(M_4)$
8. **If** $(T_3' = T_3)$ and $(h_f(PWi || Ni)' = h_f(PWi || Ni)'')$ **Then**
9. Call Reveal oracle on input n_2P to produce n_2' as $n_2' \leftarrow reveal2(n_2P)$
10. Compute $n_2P^* = h_f(PWi || Ni)' \oplus M_3$
Compute $SK = h_f(n_1'n_2'P || h_f(PWi || Ni)' || IDi)$
11. **If** $(n_2P^* = n_2'P)$ and $(IDi' = IDi)$ **Then**
12. Accept SK as rightly agreed session key for Sj and Ui.
13. Return 1 (True)
14. Else
15. Return 0 (False)
16. End if
17. End if

Theorem 3

By taking ECDLP as assumption, as one-sided hash function stands too close to a random oracle, the contributed protocol stays protected, if some attacker goes maliciously for deriving an agreed session key (SK) between participants.

Proof.

Here, we plan to set \mathcal{A} , capable of deriving the agreed session key (SK) between Sj and Ui, by engaging random oracles $Reveal1$, $Reveal2$, and running the experiment as shown in algorithm $EXP2_{PSBASME}^{HASH,SC}$. The probability of success against $EXP2_{PSBASME}^{HASH,SC}$ is $Sucss1 = \text{Pro}[EXP2_{PSBASME}^{HASH,SC} = 1] - 1$, while $\text{Pro}[E]$ shows the probability of some event E. The corresponding advantage function of the related experiment turns out to be $Adv_{PSBASME}^{HASH,SC}(t_{m1}, q_{Ry1}, q_{Ry2}) = \max_{\mathcal{A}} [Sucss1_{PSBASME}^{HASH,SC}]$, having total execution time t_{m1} , while the Reveal queries as q_{Ry1} and q_{Ry2} maximized on \mathcal{A} . We pronounce the contributed protocol as resilient to some attacker \mathcal{A} against recovering the agreed session key (SK) between Sj and Ui, provided $Adv_{PSBASME}^{HASH,SC}(t_{m1}, q_{Ry1}, q_{Ry2}) \leq \alpha$ for some adequately small $\alpha > 0$. In relation to this experiment, if \mathcal{A} is capable of reversing a one-sided function $h_f(\cdot)$, then solving the hard problem ECDLP, onwards it could comfortably derive the correct session key (SK) computed among the participants, and finally the attacker shall win the game. However, in keeping with definition (2) and (3), this would not be computationally viable to reverse $h_f(\cdot)$ and compute ECDLP, as $Adv_{PSBASME}^{HASH}$ and $Adv_{PSBASME}^{HASH,SC}(t_{m1}) \leq \alpha$ for some adequately small $\alpha > 0$. In this perspective, the contributed work stands protected in the wake of the strong secure

features of hash function and ECDLP that are evidently too intractable to solve.

7. PERFORMANCE EVALUATION

In performance analysis section, we compare the security properties of proposed scheme with other multi-server authentication schemes. **Table 2** depicts the functionality comparison and threat analysis for various techniques, while this analysis suggests the proposed model as robust against other contemporary MSA-based protocols. According to analysis, the Mishra scheme [21] is prone to forgery attack and besides, it does not conform to perfect forward secrecy. The Chuang scheme [31] lacks mutual authentication, and suffers stolen smart card and forgery attack. Likewise, He et al. scheme [24] does not offer anonymity to the user, and the scheme is prone to forgery and masquerading attacks as well, [35]. The Lu et al. scheme [32] is vulnerable to insider attack and lacks forward secrecy, as above remarked. For comparison of the computation costs, in **Table 3**, we symbolize hash operation with T_H , elliptic curve based point multiplication T_{PM} , asymmetric key encryption/decryption T_{AE}/T_{AD} , and ignoring XOR function for its insignificant cost. The computation time for different crypto-primitives by Kilinc [45] is defined in milliseconds: $T_H \approx 0.0023\text{ms}$, $T_{AE} = T_{AD} \approx 3.85\text{ms}$, and $T_{PM} \approx 2.226\text{ms}$. The comparison in **Table 2** entails Mishra et al., He et al., Chuang et al., Lu et al., and our proposed scheme.

Table 2. Functionality Comparison for different MSA-based schemes

	[21]	[24]	[31]	[32]	Ours
Provides Anonymity	✓	×	✓	✓	✓
Provides Mutual Authentication	✓	✓	×	✓	✓
Resists Insider Attack	✓	✓	✓	×	✓
Resists Forgery Attack	×	×	×	✓	✓
Resists Offline password guessing attack	✓	✓	✓	✓	✓
Resists Stolen smart card attack	✓	✓	×	✓	✓
Resists Masquerading attack	✓	×	✓	✓	✓
Resists Replay attack	✓	✓	✓	✓	✓
Provides Session key agreement	✓	✓	✓	✓	✓
Compliant to Perfect forward secrecy	×	✓	✓	×	✓

✓ protected against attack or corresponding weakness.

× exposed to some attack or prone to corresponding weakness.

Table 3. Number of operations

		[21]	[24]	[31]	[32]	Ours
Registration		$5\ T_H$	$2\ T_H$	$3\ T_H$	$3\ T_H$	$5\ T_H$
Authentication	User	$8\ T_H$	$7\ T_H + 3T_{PM}$	$8\ T_H$	$4T_H + 1T_{AE}$	$5\ T_H + 1T_{AE} + 1T_{PM}$
	Server	$6\ T_H$	$5\ T_H + 2\ T_{PM}$	$7\ T_H$	$4T_H + 1T_{AD}$	$3T_H + 1T_{AD} + 1T_{PM}$
	RC	-	$9T_H + 2\ T_{PM}$	-	-	-
Total		$14\ T_H$ $\approx 0.0322ms$	$21\ T_H + 7\ T_{PM}$ $\approx 15.6303ms$	$15\ T_H$ $\approx 0.0345ms$	$8T_H + 1T_{AD} + 1T_{AE}$ $\approx 7.7184ms$	$8\ T_H + 2T_{AE} + 2T_{PM}$ $\approx 12.1704ms$
Password Modification		$3\ T_H$	$2\ T_H$	$3\ T_H$	$3\ T_H$	$3\ T_H$

The computational cost for [21, 24, 31, 32] is compared against the proposed scheme. Although, the computational cost for [21, 31, 32] is quite low for the use of T_H and T_{AE} based operations, the schemes are susceptible to several attacks, as illustrated in Table 2. The He et al.'s scheme [24] is a costly scheme for having $8T_{PM}$ operations in a single iteration of the scheme, despite, the scheme is vulnerable to three attacks as shown above. Although, the proposed protocol comprises two additional T_{PM} operations as compared with [32], yet the proposed protocol is resistant to user impersonation attack and perfect forward secrecy violation. A bit extra cost could be afforded to enhance and improve the security of the protocol. We assume that the communication cost for various crypto-operations, i.e., elliptic curve scalar point is 320-bits, hash-based digest (SHA-1) is 160-bits, user or server's identity is 160-bits, randomly generated number is 160-bits, timestamp is 32-bits and AES encryption is 128-bits [44]. The communication cost for proposed scheme is remarkably lower than other counterparts as depicted in Table 4, which ensures the efficiency of the proposed work.

Table 4. Comparison of communication overhead

	No. of Messages	Cost (Bits)
Mishra [21]	(3)	1280
He [24]	(5)	3200
Chuang [31]	(3)	1280
Lu [32]	(3)	768
Ours	(2)	672

Thus, in view of given performance evaluation, we analyze that our proposed model is more resistant to threats than other protocols including Lu et al.'s scheme with a little bit more cost, though necessary. Since, without those extra cryptographic operations like T_{PM} , it might be improbable to bring the perfect forward secrecy in the scheme that also resist against insider attacks.

8. CONCLUSION

The multi-server authenticated key agreement is considered a critical requirement of the crucial requirement of the current internet-based authentication framework. In this work, we reviewed Lu et al.'s scheme which is a multi-server authentication protocol and is found to be vulnerable to many threats. The cryptanalysis revealed that the scheme could be exposed in two ways: malicious insider attack and perfect forward secrecy incompliance. Our proposal counters the identified threats and introduced an improved scheme. This scheme is duly analyzed against the threats using automated tools and formal security procedures, and also evaluated the results with other contemporary MSA-based schemes.

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