

An efficient dynamic ID based remote user authentication scheme using self-certified public keys for multi-server environment

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Abstract. Recently, Li et al. analyzed Lee et al.'s multi-server authentication scheme and proposed a novel smart card and dynamic ID based remote user authentication scheme for multi-server environments. They claimed that their scheme can resist several kinds of attacks. However, through careful analysis, we find that Li et al.'s scheme is vulnerable to stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack. By analyzing other similar schemes, we find that the certain type of dynamic ID based multi-server authentication scheme in which only hash functions are used and no registration center participates in the authentication and session key agreement phase is hard to provide perfect efficient and secure authentication. To compensate for these shortcomings, we improve the recently proposed Liao et al.'s multi-server authentication scheme which is based on pairing and self-certified public keys, and propose a novel dynamic ID based remote user authentication scheme for multi-server environments. Liao et al.'s scheme is found vulnerable to offline dictionary attack and denial of service attack, and cannot provide user's anonymity and local password verification. However, our proposed scheme overcomes the shortcomings of Liao et al.'s scheme. Security and performance analyses show the proposed scheme is secure against various attacks and has many excellent features.

Keyword. Authentication, Multi-server, Pairing-based, Hash function, Self-certified public keys.

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§1 Introduction

With the rapid development of network technologies, more and more people begin using the network to acquire various services such as on-line financial, on-line medical, on-line shopping, on-line bill payment, on-line documentation and data exchange, etc. And the architecture of server providing services to be accessed over the network often consists of many different servers around the world instead of just one. While enjoying the comfort and convenience of the internet, people are facing with the emerging challenges from the network security.

Identity authentication is the key security issue of various types of on-line applications and service systems. Before an user accessing the services provided by a service provider server, mutual identity authentication between the user and the server is needed to prevent the unauthorized personnel from accessing services provided by the server and avoid the illegal system cheating the user by masquerading as legal server. In the single server environment, password based authentication scheme [1] and its enhanced version which additionally uses smart cards [2-9] are widely used to provide mutual authentication between the users and servers. However, the conventional password based authentication methods are not suitable for the multi-servers environment since each user does not only need to log into different remote servers repetitively but also need to remember many various sets of identities and passwords if he/she wants to access these service providing servers. In order to resolve this problem, in 2000, based on the difficulty of factorization and hash function, Lee and Chang [10] proposed a user identification and key distribution scheme which agrees with the multi-server environment. Since then, authentication schemes for the multi-server environment have been widely investigated and designed by many researchers [11-28].

Based on the used of the basic cryptographic algorithms, the existing multi-server authentication schemes can be divided into two types, namely the hash based authentication schemes and the public-key based authentication schemes. At the same time, among these existing multi-server authentication schemes, some of them need the registration center (RC) to participate in the authentication and session key agreement phase, while others don't. Therefore, according to the participation or not of the RC in the authentication and session key agreement phase, we divide the multi-server authentication schemes into RC depended authentication schemes and non-RC depended authentication schemes.

In this paper, we analyze a novel multi-server authentication scheme, Li et al.'s scheme [20] which is only based on hash function and a non-RC depended authentication scheme. We find that this scheme is vulnerable to stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack. By analyzing some other similar schemes [15,17-19], we find that the type of dynamic ID based multi-server authentication scheme which is only using hash functions and non-RC depended is hard to provide perfect efficient and secure authentication. To compensate for these shortcomings, we improve the recently proposed Liao et al.'s multi-server authentication scheme [27] which is based on pairing and self-certified public keys, and propose a novel dynamic ID based remote user authentication scheme for multi-server environments. Liao et al.'s scheme is found vulnerable to offline dictionary attack

[28] and denial of service attack, and cannot provide user's anonymity and local password verification. However, our proposed scheme overcomes the shortcomings of Liao et al.'s scheme. Security and performance analyses show the proposed scheme is secure against various attacks and has many excellent features.

§2 Related works

A large number of authentication schemes have been proposed for the multi-server environment. Hash function is one of the key technologies in the construction of multi-server authentication scheme. In 2004, Juang et al. [11] proposed an efficient multi-server password authenticated key agreement scheme based on a hash function and symmetric key cryptosystem. In 2009, Hsiang and Shih [12] proposed a dynamic ID based remote user authentication scheme for multi-server environment in which only hash function is used. However, Sood et al. [13] found that Hsiang and Shih's scheme is susceptible to replay attack, impersonation attack and stolen smart card attack. Moreover, the password change phase of Hsiang and Shih's scheme is incorrect. Then Sood et al. presented a novel dynamic identity based authentication protocol for multi-server architecture to resolve the security flaws of Hsiang and Shih's scheme [13]. After that, Li et al. [14] pointed out that Sood et al.'s protocol is still vulnerable to leak-of-verifier attack, stolen smart card attack and impersonation attack. At the same time, Li et al. [14] proposed another dynamic identity based authentication protocol for multi-server architecture. However, the above mentioned scheme are all RC dependent multi-server authentication scheme. In 2009, Liao and Wang [15] proposed a dynamic ID based multi-server authentication scheme which is based on hash function and non-RC dependent. But, Liao and Wang's scheme is vulnerable to insider's attack, masquerade attack, server spoofing attack, registration center spoofing attack and is not repairable [16]. After that, Shao et al. [17] and Lee et al. [18,19] proposed some similar types of multi-server authentication schemes. In 2012, Li et al.[20] pointed out that Lee et al.'s scheme [18] cannot withstand forgery attack, server spoofing attack and cannot provide proper authentication, and then proposed a novel dynamic ID based multi-server authentication schemes which is only using hash function and non-RC dependent. However, with careful analysis, we find that Li et al.'s scheme [20] is still vulnerable to stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack. We also analyzed Shao et al.'s scheme [17] and Lee et al.'s scheme [19], they are all vulnerable to stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack. In general, it is difficult to construct a secure dynamic ID based and non-RC dependent multi-server authentication scheme if only hash functions are used.

Public-key cryptograph is another useful technique which is widely used in the construction of multi-server authentication scheme. In 2000, Lee and Chang [21] proposed a user identification and key distribution scheme in which the difficulty of factorization on public key cryptography is used. In 2001, Tsaur [22] proposed a remote user authentication scheme based on RSA cryptosystem and Lagrange interpolating polynomial for multi-server environments. Then

Lin et al. [23] proposed a multi-server authentication protocol based on the simple geometric properties of the Euclidean and discrete logarithm problem concept. Since the traditionally public key cryptographic algorithms require many expensive computations and consume a lot of energy, Geng and Zhang [24] proposed a dynamic ID-based user authentication and key agreement scheme for multi-server environment using bilinear pairings. But Geng and Zhang's scheme cannot withstand user spoofing attack [25]. After that, Tseng et al. [26] proposed an efficient pairing-based user authentication scheme with smart cards. However, in 2013, Liao and Hsiao [27] pointed out that Tseng et al.'s scheme is vulnerable to insider attack, offline dictionary attack and malicious server attack, and cannot provide proper mutual authentication and session key agreement. At the same time, Liao and Hsiao proposed a novel non-RC depended multi-server remote user authentication scheme using self-certified public keys for mobile clients [27]. Recently, Chou et al. [28] found Liao and Hsiao's scheme cannot withstand password guessing attack. Furthermore, with careful analysis, we find that Liao and Hsiao's scheme is still vulnerable to denial of service attack, and cannot provide user's anonymity and local password verification. In this paper, based on the Liao and Hsiao's scheme, we propose a secure dynamic ID based and non-RC depended multi-server authentication scheme using the pairing and self-certified public keys.

§3 Review and cryptanalysis of Li et al.'s authentication scheme

3.1 Review of Li et al.'s scheme

Li et al.'s contains three participants, the user U_i , the server S_j , and the registration center RC . RC chooses the master secret key x and a secret number y to compute $h(x||y)$ and $h(SID_j||h(y))$, and then shares them with S_j via a secure channel. SID_j is the identity of server S_j . There are four phases in the scheme: registration phase, login phase, verification phase, and password change phase.

3.1.1 Registration phase

When the remote user authentication scheme starts, the user U_i and the registration center RC need to perform the following steps to finish the registration phase:

(1) U_i freely chooses his/her identity ID_i , the password PW_i , and computes $A_i = h(b \oplus PW_i)$, where b is a random number generated by U_i . Then U_i sends ID_i and A_i to the registration center RC for registration through a secure channel.

(2) RC computes $B_i = h(ID_i||x)$, $C_i = h(ID_i||h(y)||A_i)$, $D_i = h(B_i||h(x||y))$ and $E_i = B_i \oplus h(x||y)$. RC stores $\{C_i, D_i, E_i, h(\cdot), h(y)\}$ on the user's smart card and sends it to user U_i via a secure channel.

(3) U_i keys b into the smart card, and finally the smart card contains $\{C_i, D_i, E_i, b, h(\cdot), h(y)\}$.

3.1.2 Login phase

Whenever U_i wants to login S_j , he/she must perform the following steps to generate a login request message:

- (1) U_i inserts his/her smart card into the card reader and inputs ID_i and PW_i . Then the smart card computes $A_i = h(b \oplus PW_i)$, $C_i^* = h(ID_i \| h(y) \| A_i)$, and checks whether the computed C_i^* is equal to C_i . If they are equal, U_i proceeds the following steps. Otherwise the smart card aborts the session.
- (2) The smart card generates a random number N_i and computes $P_{ij} = E_i \oplus h(h(SID_j \| h(y)) \| N_i)$, $CID_i = A_i \oplus h(D_i \| SID_j \| N_i)$, $M_1 = h(P_{ij} \| CID_i \| D_i \| N_i)$ and $M_2 = h(SID_j \| h(y)) \oplus N_i$.
- (3) U_i submits $\{P_{ij}, CID_i, M_1, M_2\}$ to S_j as a login request message.

3.1.3 Verification phase

When S_j receiving the login message $\{P_{ij}, CID_i, M_1, M_2\}$, S_j and U_i perform the following steps to finish the mutual authentication and session key agreement.

- (1) S_j computes $N_i = M_2 \oplus h(SID_j \| h(y))$, $E_i = P_{ij} \oplus h(h(SID_j \| h(y)) \| N_i)$, $B_i = E_i \oplus h(x \| y)$, $D_i = h(B_i \| h(x \| y))$ and $A_i = CID_i \oplus h(D_i \| SID_j \| N_i)$ by using $\{P_{ij}, CID_i, M_1, M_2\}$, $h(SID_j \| h(y))$ and $h(x \| y)$.
- (2) S_j computes $h(P_{ij} \| CID_i \| D_i \| N_i)$ and checks whether it is equal to M_1 . If they are not equal, S_j rejects the login request and terminates this session. Otherwise, S_j accepts the login request message. Then S_j generates a random number N_j and computes $M_3 = h(D_i \| A_i \| N_j \| SID_j)$, $M_4 = A_i \oplus N_i \oplus N_j$. Finally, S_j sends the message $\{M_3, M_4\}$ to U_i .
- (3) After receiving the response message $\{M_3, M_4\}$ sent from S_j , U_i computes $N_j = A_i \oplus N_i \oplus M_4$, $M_3^* = h(D_i \| A_i \| N_j \| SID_j)$ and checks M_3^* with the received message M_3 . If they are not equal, U_i rejects these messages and terminates this session. Otherwise, U_i successfully authenticates S_j . Then, the user U_i computes the mutual authentication message $M_5 = h(D_i \| A_i \| N_i \| SID_j)$ and sends $\{M_5\}$ to the server S_j .
- (4) Upon receiving the message $\{M_5\}$ from U_i , S_j computes $h(D_i \| A_i \| N_i \| SID_j)$ and checks it with the received message $\{M_5\}$. If they are equal, S_j successfully authenticates U_i and the mutual authentication is completed. After the mutual authentication phase, the user U_i and the server S_j compute $SK = h(D_i \| A_i \| N_i \| N_j \| SID_j)$, which is taken as their session key for future secure communication.

3.1.4 Password change phase

This phase is invoked whenever U_i wants to change his password PW_i to a new password PW_i^{new} . There is no need for a secure channel for password change, and it can be finished without communicating with the registration center RC .

- (1) U_i inserts his/her smart card into the card reader and inputs ID_i and PW_i .
- (2) The smart card computes $A_i = h(b \oplus PW_i)$, $C_i^* = h(ID_i \| h(y) \| A_i)$, and checks whether the computed C_i^* is equal to C_i . If they are not equal, the smart card rejects the password

change request. Otherwise, the user U_i inputs a new password PW_i^{new} and a new random number b^{new} .

(3) The smart card computes $A_i^{new} = h(b^{new} \oplus PW_i^{new})$ and $C_i^{new} = h(ID_i \| h(y) \| A_i^{new})$.

(4) Finally, the smart card replaces C_i and b with C_i^{new} and b^{new} to finish the password change phase.

3.2 Cryptanalysis of Li et al.'s scheme

Li et al. claimed that their scheme can resist many types of attacks and satisfy all the essential requirements for multi-server architecture authentication. However, if we assume that A is an adversary who has broken a user U_m and a server S_n , or a combination of a malicious user U_m and a dishonest server S_n . Then A could get the secret number $h(x\|y)$ and $h(y)$, and can perform the stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack to Li et al.'s scheme. The concrete cryptanalysis of the Li et al.'s scheme is shown as follows.

3.2.1 Stolen smart card and offline dictionary attack

If a user U_i 's smart card is stolen by an adversary A , A can extract the information $\{C_i, D_i, E_i, b, h(\cdot), h(y)\}$ from the memory of the stolen smart card. Furthermore, in case A intercepts a valid login request message $\{P_{ij}, CID_i, M_1, M_2\}$ sent from user U_i to server S_j in the public communication channel, A can compute $N_i = h(SID_j \| h(y)) \oplus M_2$, $E_i = P_{ij} \oplus h(h(SID_j \| h(y)) \| N_i)$, $B_i = E_i \oplus h(x\|y)$, $D_i = h(B_i \| h(x\|y))$ and $A_i = CID_i \oplus h(D_i \| SID_j \| N_i)$ by using $h(y)$ and $h(x\|y)$. Then A can launch offline dictionary attack on $C_i = h(ID_i \| h(y) \| A_i)$ to know the identity ID_i of the user U_i because A knows the values of A_i corresponding to the user U_i . Besides A can launch offline dictionary attack on $A_i = h(b \oplus PW_i)$ to know the password PW_i of U_i because A knows the value of b from the stolen smart card of the user U_i . Now A possesses the valid smart card of user U_i , knows the identity ID_i , password PW_i corresponding to the user U_i and hence can login on to any service server.

3.2.2 Replay attack

The replay attack is replaying the same message of the receiver or the sender again. If adversary A has intercepted a valid login request message $\{P_{ij}, CID_i, M_1, M_2\}$ sent from user U_i to server S_j in the public communication channel. Then A can compute $N_i = h(SID_j \| h(y)) \oplus M_2$, $E_i = P_{ij} \oplus h(h(SID_j \| h(y)) \| N_i)$, $B_i = E_i \oplus h(x\|y)$, $D_i = h(B_i \| h(x\|y))$ and $A_i = CID_i \oplus h(D_i \| SID_j \| N_i)$ by using $h(y)$ and $h(x\|y)$. Then adversary A can replay this login request message $\{P_{ij}, CID_i, M_1, M_2\}$ to S_j by masquerading as the user U_i at some time latter. After verification of the login request message, S_j computes $M_3 = h(D_i \| A_i \| N_j \| SID_j)$ and $M_4 = A_i \oplus N_i \oplus N_j$, and sends the message $\{M_3, M_4\}$ to A who is masquerading as the user U_i . The adversary A can verify the received value of $\{M_3, M_4\}$ and compute $M'_5 = h(D_i \| A_i \| N_i \| SID_j)$ since he knows the values of N_i, E_i, B_i, D_i and A_i . Then A sends $\{M'_5\}$ to the server S_j . The S_j

computes $h(D_i\|A_i\|N_i\|SID_j)$ and checks it with the received message $\{M'_5\}$. This equivalency authenticates the legitimacy of the user U_i , the service provider server S_j and the login request is accepted. Finally after mutual authentication, adversary A masquerading as the user U_i and the server S_j agree on the common session key as $SK = h(D_i\|A_i\|N_i\|N_j\|SID_j)$. Therefore, the adversary A can masquerade as user U_i to login on to server S_j by replaying the same login request message which had been sent from U_i to S_j .

3.2.3 Impersonation attack

In this subsection, we show that the adversary A who possesses $h(y)$ and $h(x\|y)$ can masquerade as any user U_i to login any server S_j as follows.

Adversary A chooses two random numbers a_i and b_i , and computes $A_i = h(a_i)$ and $B_i = h(b_i)$. Then A can compute $D_i = h(B_i\|h(x\|y))$, $E_i = B_i \oplus h(x\|y)$, $P_{ij} = E_i \oplus h(h(SID_j\|h(y))\|N_i)$, $CID_i = A_i \oplus h(D_i\|SID_j\|N_i)$, $M_1 = h(P_{ij}\|CID_i\|D_i\|N_i)$ and $M_2 = h(SID_j\|h(y)) \oplus N_i$ by using $h(y)$ and $h(x\|y)$. Now A sends the login request message $\{P_{ij}, CID_i, M_1, M_2\}$ by masquerading as the user U_i to server S_j . After receiving the login request message, S_j computes $N_i = h(SID_j\|h(y)) \oplus M_2$, $E_i = P_{ij} \oplus h(h(SID_j\|h(y))\|N_i)$, $B_i = E_i \oplus h(x\|y)$, $D_i = h(B_i\|h(x\|y))$ and $A_i = CID_i \oplus h(D_i\|SID_j\|N_i)$ by using $\{P_{ij}, CID_i, M_1, M_2\}$, $h(x\|y)$ and $h(SID_j\|h(y))$. Then S_j computes $M_3 = h(D_i\|A_i\|N_j\|SID_j)$ and $M_4 = A_i \oplus N_i \oplus N_j$, and sends the message $\{M_3, M_4\}$ to A who is masquerading as the user U_i . Then adversary A computes $N_j = A_i \oplus N_i \oplus M_4$ and verifies M_3 by computing $h(D_i\|A_i\|N_j\|SID_j)$. Then A computes $M_5 = h(D_i\|A_i\|N_i\|SID_j)$ and sends $\{M_5\}$ back to the server S_j . The S_j computes $h(D_i\|A_i\|N_i\|SID_j)$ and checks it with the received message $\{M_5\}$. This equivalency authenticates the legitimacy of the user U_i , the service provider server S_j and the login request is accepted. Finally after mutual authentication, adversary A masquerading as the user U_i and the server S_j agree on the common session key as $SK = h(D_i\|A_i\|N_i\|N_j\|SID_j)$.

3.2.4 Server spoofing attack

In this subsection, we show that the adversary A who possesses $h(y)$ and $h(x\|y)$ can masquerade as the server S_j to spoof user U_i , if A has intercepted a valid login request message $\{P_{ij}, CID_i, M_1, M_2\}$ sent from user U_i to server S_j in the public communication channel.

After intercepting a valid login request message $\{P_{ij}, CID_i, M_1, M_2\}$ sent from user U_i to server S_j in the public communication channel, A can compute $N_i = h(SID_j\|h(y)) \oplus M_2$, $E_i = P_{ij} \oplus h(h(SID_j\|h(y))\|N_i)$, $B_i = E_i \oplus h(x\|y)$, $D_i = h(B_i\|h(x\|y))$ and $A_i = CID_i \oplus h(D_i\|SID_j\|N_i)$ corresponding to U_i . Then A can choose a random number N'_j , and compute $M_3 = h(D_i\|A_i\|N'_j\|SID_j)$ and $M_4 = A_i \oplus N_i \oplus N'_j$. A then sends the message $\{M_3, M_4\}$ by masquerading as server S_j to the user U_i . After receiving the message $\{M_3, M_4\}$, U_i computes $N'_j = A_i \oplus N_i \oplus M_4$ and verifies M_3 by computing $h(D_i\|A_i\|N'_j\|SID_j)$. Then U_i computes $M_5 = h(D_i\|A_i\|N_i\|SID_j)$ and sends it to the S_j who is masquerading as the adversary A . Then A computes $h(D_i\|A_i\|N_i\|SID_j)$ and checks it with the received message $\{M_5\}$. Finally

after mutual authentication, adversary A masquerading as the server S_j and the user U_i agree on the common session key as $SK = h(D_i \| A_i \| N_i \| N'_j \| SID_j)$.

3.3 Discussion

Except the Li et al.'s scheme, we also analyzed other four dynamic ID based authentication schemes for multi-server environment [15,17-19]. These schemes are all based on hash functions and non-RC dependent. We found that such type of multi-server remote user authentication scheme are almost vulnerable to stolen smart card and offline dictionary attacks, impersonation attack and server spoofing attack etc. The cryptanalysis methods of these schemes are similar to that of Li et al.'s scheme shown in section 3.2. We think that under the assumptions that no registration center participates in the authentication and session key agreement phase, the dynamic ID and hash function based user authentication schemes for multi-server environment is hard to provide perfect efficient and secure authentication. Fortunately, there is another technique, public-key cryptograph which is widely used in the construction of authentication scheme. Therefore, in order to construct a secure, low power consumption and non-RC dependent authentication scheme, we adopt the elliptic curve cryptographic technology of public-key techniques, and propose a novel dynamic ID based and non-RC dependent remote user authentication scheme using pairing and self-certified public keys for multi-server environment.

§4 Preliminaries

Before presenting our scheme, we introduce the concepts of bilinear pairings, self-certified public keys, as well as some related mathematical assumptions.

4.1 Bilinear pairings

Let G_1 be an additive cyclic group with a large prime order q and G_2 be a multiplicative cyclic group with the same order q . Particularly, G_1 is a subgroup of the group of points on an elliptic curve over a finite field $E(F_p)$ and G_2 is a subgroup of the multiplicative group over a finite field. P is a generator of G_1 .

A bilinear pairing is a map $e : G_1 \times G_1 \rightarrow G_2$ and satisfies the following properties:

- (1) Bilinear: $e(aP, bQ) = e(P, Q)^{ab}$ for all $P, Q \in G_1$ and $a, b \in Z_q^*$.
- (2) Non-degenerate: There exists $P, Q \in G_1$ such that $e(P, Q) \neq 1$.
- (3) Computability: There is an efficient algorithm to compute $e(P, Q)$ for all $P, Q \in G_1$.

4.2 self-certified public keys

In [27], Liao et al. first proposes a key distribution based on self-certified public keys (SCPks) [29,30] among the service servers. By using the SCPK, a user's public key can be computed directly from the signature of the third trust party (TTP) on the user's identity instead of

verifying the public key using an explicit signature on a user's public key. The SCPK scheme is described as follows.

(1) Initialization: The third trust party (TTP) first generates all the needed parameters of the scheme. TTP chooses a non-singular high elliptic curve $E(F_p)$ defined over a finite field, which is used with a based point generator P of prime order q . Then TTP freely chooses his/her secret key s_T and computes his/her public key $pub_T = s_T \cdot P$. The related parameters and pub_T are publicly and authentically available.

(2) Private key generation: An user A chooses a random number k_A , computes $K_A = k_A \cdot P$ and sends his/her identity ID_A and K_A to the TTP. TTP chooses a random number r_A , computes $W_A = K_A + r_A \cdot P$ and $\bar{s}_A = h(ID_A \parallel W_A) + r_A$, and sends W_A and \bar{s}_A to user A . Then A obtains his/her secret key by calculating $s_A = \bar{s}_A + k_A$.

(3) Public key extraction: Anyone can calculate A 's public key $pub_A = h(ID_A \parallel W_A)pub_T + W_A$ when he/she receives W_A .

4.3 Related mathematical assumptions

To prove the security of our proposed protocol, we present some important mathematical problems and assumptions for bilinear pairings defined on elliptic curves. The related concrete description can be found in [31,32].

(1) Computational discrete logarithm (CDL) problem: Given $R = x \cdot P$, where $P, R \in G_1$. It is easy to calculate R given x and P , but it is hard to determine x given P and R .

(2) Elliptic curve factorization (ECF) problem: Given two points P and $R = x \cdot P + y \cdot P$ for $x, y \in Z_q^*$, it is hard to find $x \cdot P$ and $y \cdot P$.

(3) Computational Diffie-Hellman (CDH) problem: Given $P, xP, yP \in G_1$, it is hard to compute $xyP \in G_1$.

§5 The proposed scheme

In this section, by improving the recently proposed Liao et al.'s multi-server authentication scheme [27] which is found vulnerable to offline dictionary attack and denial of service attack [28], and cannot provide user's anonymity and local password verification, we propose a novel dynamic ID based remote user authentication scheme for multi-server environment using pairing and self-certified public keys. Our scheme contains three participants: the user U_i , the service provider server S_j , and the registration center RC . The legitimate user U_i can easily login on to the service provider server using his smart card, identity and password. There are six phases in the proposed scheme: system initialization phase, the user registration phase, the server registration phase, the login phase, the authentication and session key agreement phase, and the password change phase. The notations used in our proposed scheme are summarized in Table 1.

Table 1: Notations used in the proposed scheme.

e	A bilinear map, $e : G_1 \times G_1 \longrightarrow G_2$.
U_i	The i th user.
ID_i	The identity of the user U_i .
S_j	The j th service provider server.
SID_j	The identity of the service provider server S_j .
RC	The registration center.
s_{RC}	The master secret key of the registration center RC in Z_q^* .
pub_{RC}	The public key of RC , $pub_{RC} = s_{RC} \cdot P$.
P	A generator of group G_1 .
$H()$	A map-to-point function, $H : 0, 1^* \longrightarrow G_1$.
$h()$	A one way hash function, $h : 0, 1^* \longrightarrow 0, 1^k$, where k is the output length. $h()$ allows the concatenation of some integer values and points on an elliptic curve.
\oplus	A simple XOR operation in G_1 . If $P_1, P_2 \in G_1$, P_1 and P_2 are points on an elliptic curve over a finite field, the operation $P_1 \oplus P_2$ means that it performs the XOR operations of the x-coordinates and y-coordinates of P_1 and P_2 , respectively.
\parallel	The concatenation operation.

5.1 System initialization phase

In the proposed scheme, registration center RC is assumed a third trust party. In the system initialization phase, RC generates all the needed parameters of the scheme.

(1) RC selects a cyclic additive group G_1 of prime order q , a cyclic multiplicative group G_2 of the same order q , a generator P of G_1 , and a bilinear map $e : G_1 \times G_1 \longrightarrow G_2$.

(2) RC freely chooses a number $s_{RC} \in Z_q^*$ keeping as the system private key and computes $pub_{RC} = s_{RC} \cdot P$ as the system public key.

(3) RC selects two cryptographic hash functions $H(\cdot)$ and $h(\cdot)$.

Finally, all the related parameters $\{e, G_1, G_2, q, P, Pub_{RC}, H(\cdot), h(\cdot)\}$ are publicly and authentically available.

5.2 User registration phase

When the user U_i wants to access the services, he/she has to submit his/her some related information to the registration center RC for registration. The steps of the user registration phase are as follows:

(1) The user U_i freely chooses his/her identity ID_i and password pw_i , and chooses a random number b_i . Then U_i computes $HPW_i = h(ID_i \parallel pw_i \parallel b_i) \cdot P$, and submits ID_i and HPW_i to RC for registration via a secure channel.

(2) When receiving the message ID_i and HPW_i , RC computes $QID_i = H(ID_i)$, $CID_i = s_{RC} \cdot QID_i$, $Reg_{ID_i} = CID_i \oplus s_{RC} \cdot HPW_i$ and $H_i = h(QID_i \parallel CID_i)$. Then RC stores the message $\{Reg_{ID_i}, H_i\}$ in U_i 's smart card and submits the smart card to U_i through a secure channel.

(3) After receiving the smart card, U_i enters b_i into the smart card. Finally, the smart card contains parameters $\{Reg_{ID_i}, H_i, b_i\}$.

5.3 Server registration phase

If a service provider server S_j wants to provides services for the users, he/she must perform the registration to the registration center RC to become a legal service provider server. The process of server registration phase of the proposed scheme is based on SCPK mentioned in section 4.2.

(1) S_j chooses a random number v_j and computes $V_j = v_j \cdot P$. Then S_j submits SID_j and V_j to RC for registration via a secure channel.

(2) After receiving the message $\{SID_j, V_j\}$, RC chooses a random number w_j , and computes $W_j = w_j \cdot P + V_j$ and $s'_j = (s_{RC} \cdot h(SID_j \parallel W_j) + w_j) \bmod q$. Then RC submits the message $\{W_j, s'_j\}$ to S_j through a secure channel.

(3) After receiving $\{W_j, s'_j\}$, S_j computes the private key $s_j = (s'_j + v_j) \bmod q$, and checks the validity of the values issued to him/her by checking the following equation: $pub_j = s_j \cdot P = h(SID_j \parallel W_j) \cdot pub_{RC} + W_j$. At last, S_j 's personal information contains $\{SID_j, pub_j, s_j, W_j\}$

The details of user registration phase and server registration phase are shown in Fig.1.

5.4 Login phase

If user U_i wants to access the services provided by server S_j , U_i needs to login on to S_j , the process of the login phase are as following:

(1) U_i inserts his/her smart card into the smart card reader, and inputs identity ID_i and password pw_i . Then the smart card computes $QID_i = H(ID_i)$, $CID_i = Reg_{ID_i} \oplus h(ID_i \parallel pw_i \parallel b_i) \cdot pub_{RC}$, $H_i^* = h(QID_i \parallel CID_i)$, and checks whether $H_i^* = H_i$. If they are equal, it means U_i is a legal user. Otherwise the smart card aborts the session.

(2) The smart card generates two random numbers u_i and r_i , and computes $DID_i = u_i \cdot QID_i$ and $R_i = r_i \cdot P$. Then the smart card sends the login request message $\{DID_i, R_i\}$ to server S_j over a public channel.

5.5 Authentication and session key agreement phase

(1) After receiving the login request $\{DID_i, R_i\}$ sent from U_i , S_j chooses a random number r_j , and computes $R_j = r_j \cdot P$, $T_{ji} = r_j \cdot R_i$, $K_{ji} = s_j \cdot R_i$ and $Auth_{ji} = h(DID_i \parallel SID_j \parallel K_{ji} \parallel R_j)$. Then S_j sends the message $\{W_j, R_j, Auth_{ji}\}$ to U_i .

(2) When receiving $\{W_j, R_j, Auth_{ji}\}$, U_i computes $T_{ij} = r_i \cdot R_j$, $pub_j = h(SID_j \parallel W_j) \cdot pub_{RC} + W_j$, $K_{ij} = r_i \cdot pub_j$ and $Auth_{ij} = h(DID_i \parallel SID_j \parallel K_{ij} \parallel R_j)$. Then U_i checks $Auth_{ij}$

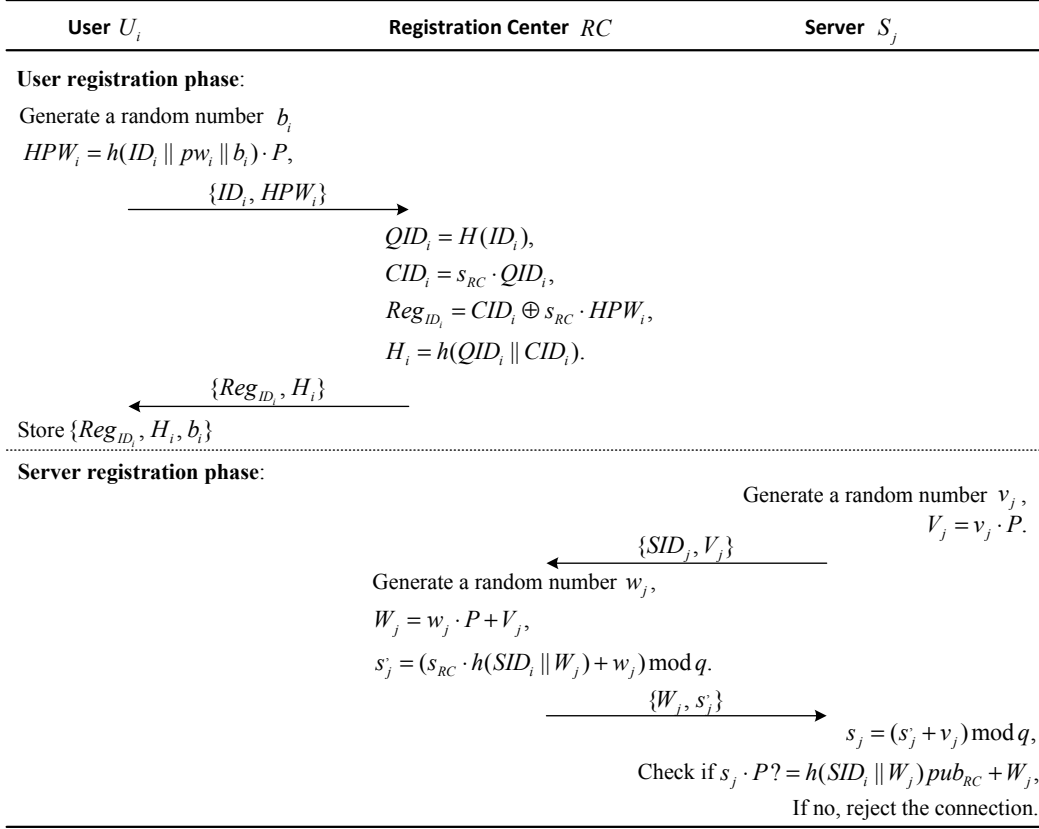


Figure 1: User and server registration phase of the proposed scheme.

with the received $Auth_{ji}$. If they are not equal, U_i terminates this session. Otherwise, S_j is authenticated, and U_i continues to compute $M_i = r_i \cdot DID_i$, $N_i = u_i \cdot CID_i$, $d_{ij} = h(DID_i \parallel SID_j \parallel K_{ij} \parallel M_i)$ and $B_i = (r_i + d_{ij}) \cdot N_i$. Finally, U_i sends the message $\{M_i, B_i\}$ to S_j .

(3) After receiving the message $\{M_i, B_i\}$ sent from U_i , S_j computes $d_{ji} = h(DID_i \parallel SID_j \parallel K_{ji} \parallel M_i)$ and checks whether $e(M_i + d_{ji} \cdot DID_i, pub_{RC}) = e(B_i, P)$. If they are not equal, S_j terminates this session. Otherwise, U_i is authenticated.

Finally, the user U_i and the server S_j agree on a common session key as $U_i : SK = h(DID_i \parallel SID_j \parallel K_{ij} \parallel T_{ij})$, $S_j : SK = h(DID_i \parallel SID_j \parallel K_{ji} \parallel T_{ji})$.

The login phase and authentication and session key agreement phase are depicted in Fig.2.

5.6 Password change phase

The following steps show the process of the password change phase of a user U_i .

(1) The user U_i inserts his/her smart card into the smart card reader, and inputs identity ID_i and password pw_i . Then the smart card computes $QID_i = H(ID_i)$, $CID_i = Reg_{ID_i} \oplus h(ID_i \parallel pw_i \parallel b_i) \cdot pub_{RC}$, $H_i^* = h(QID_i \parallel CID_i)$, and checks whether $H_i^* = H_i$. If they are equal, it

means U_i is a legal user. Otherwise the smart card aborts the session.

(2) The smart card generates a random number z_i , and computes $Z_i = z_i \cdot P$ and $AID_i = CID_i \oplus z_i \cdot pub_{RC}$. Then the smart card sends the message $\{ID_i, AID_i, Z_i\}$ to the registration center RC .

(3) After receiving the message $\{ID_i, AID_i, Z_i\}$, RC computes $CID_i = AID_i \oplus s_{RC} \cdot Z_i$, $QID_i = H(ID_i)$, and checks whether $e(CID_i, P) = e(QID_i, pub_{RC})$. If they are equal, user U_i is authenticated. Then RC computes $V_1 = h(CID_i \parallel s_{RC} \cdot Z_i)$ and sends $\{V_1\}$ to U_i .

(4) When receiving $\{V_1\}$, user computes $h(CID_i \parallel z_i \cdot pub_{RC})$ and checks it with the received V_1 . If they are equal, the registration center RC is authenticated. Then U_i chooses his/her new password pw_i^{new} and the new random number b_i^{new} , and computes $HPW_i^{new} = h(ID_i \parallel pw_i^{new} \parallel b_i^{new}) \cdot P$, $V_2 = HPW_i^{new} \oplus z_i \cdot pub_{RC}$ and $V_3 = h(CID_i \parallel z_i \cdot pub_{RC} \parallel HPW_i^{new})$. Then U_i submits $\{V_2, V_3\}$ to RC .

(5) Upon receiving the response $\{V_2, V_3\}$, the registration server RC computes $HPW_i^{new} = V_2 \oplus s_{RC} \cdot Z_i$ and $V_3^* = h(CID_i \parallel s_{RC} \cdot Z_i \parallel HPW_i^{new})$. Then RC compares V_3^* with the received V_3 . If they are equal, RC continues to compute $Reg_{ID_i}^{new} = CID_i \oplus s_{RC} \cdot HPW_i^{new}$, $V_4 = Reg_{ID_i}^{new} \oplus s_{RC} \cdot Z_i$ and $V_5 = h(s_{RC} \cdot Z_i \parallel Reg_{ID_i}^{new})$. After that, RC sends $\{V_4, V_5\}$ to U_i .

(6) After receiving $\{V_4, V_5\}$, U_i computes $Reg_{ID_i}^{new} = V_4 \oplus z_i \cdot pub_{RC}$ and $V_5^* = h(z_i \cdot pub_{RC} \parallel Reg_{ID_i}^{new})$. Then U_i checks whether $V_5^* = V_5$. If they are equal, user U_i replaces the original Reg_{ID_i} and b_i with $Reg_{ID_i}^{new}$ and b_i^{new} .

The details of a password change phase of the proposed scheme are shown in Fig.3.

§6 Security analysis

6.1 Stolen smart card and offline dictionary attacks

In the proposed scheme, we assume that if a smart card is stolen, physical protection methods cannot prevent malicious attackers to get the stored secure elements. At the same time, adversary A can access to a big dictionary of words that likely includes user's password and intercept the communications between the user and server.

In the proposed scheme, in case a user U_i 's smart card is stolen by an adversary A , he can extract $\{Reg_{ID_i}, H_i\}$ from the memory of the stolen smart card. At the same time, it is assumed that adversary A has intercepted a previous full session messages $\{DID_i, R_i, W_j, R_j, Auth_{j_i}, M_i, B_i\}$ between the user U_i and server S_j . However, the adversary still cannot obtain the U_i 's identity ID_i and password pw_i except guessing ID_i and pw_i at the same time. Therefore, it is impossible to get the U_i 's identity ID_i and password pw_i from stolen smart card and offline dictionary attack in our proposed scheme.

6.2 Replay attack

Replaying a message of previous session into a new session is useless in our proposed scheme because user's smart card and the server choose different rand numbers r_i and r_j , and the

user's identity is different in each new session, which make all messages dynamic and valid for that session only. If we assume that an adversary A replies an intercepted previous login request $\{DID_i, R_i\}$ to S_j , after receiving the response message $\{W_j, R_j, Auth_{ji}\}$ sent from S_j , A cannot compute the correct response message $\{M_i, B_i\}$ to pass the S_j 's authentication since he does not know the values of ID_i , pw_i , u_i and r_i . Therefore, the proposed scheme is robust for the replay attack.

6.3 Impersonation attack

If an adversary A wants to masquerade as a legal user U_i to pass the authentication of a server S_j , he must have the values of both QID_i and CID_i . However, QID_i and CID_i are protected by U_i 's smart card, ID_i and pw_i since $QID_i = H(ID_i)$ and $CID_i = Reg_{ID_i} \oplus h(ID_i \parallel pw_i \parallel b_i) \cdot pub_{RC}$. Therefore, unless the adversary A can obtain the U_i 's smart card, ID_i and pw_i at the same time, the proposed scheme is secure to the impersonation attack.

6.4 Server spoofing attack

If an adversary A wants to masquerade as a legal server S_j to cheat a user U_i , he must calculate a valid $Auth_{ji}$ which is embedded with the shared secret key $K_{ji} = s_j \cdot R_i$ to pass the authentication of U_i . However, adversary A cannot derive the shared secret key K_{ji} without knowing the private key s_j of the server S_j . Therefore, our scheme is secure against the server spoofing attack.

6.5 Insider attack

In the proposed scheme, the registration center RC cannot obtain the U_i 's password pw_i . Since in the registration phase, U_i chooses a random number b_i and sends ID_i and $HPW_i = h(ID_i \parallel pw_i \parallel b_i) \cdot P$ to RC , RC can not derive pw_i from HPW_i based on CDL problem. Therefore, the proposed scheme is robust for insider attack.

6.6 Denial of service attack

In denial of service attack, an adversary A updates identity and password verification information on smart card to some arbitrary value and hence legitimate user cannot login successfully in subsequent login request to the server. In the proposed scheme, smart card checks the validity of user U_i 's identity ID_i and password pw_i before password update procedure. An adversary can insert the stolen smart card of the user U_i into smart card reader and has to guess the identity ID_i and password pw_i correctly corresponding to the user U_i . Since the smart card computes $H_i^* = h(QID_i \parallel CID_i)$, and compares it with the stored value of H_i in its memory to verify the legitimacy of the user U_i before smart card accepts password update request. It is not possible to guess identity ID_i and password pw_i correctly at the same time in real polynomial

time even after getting the smart card of the user U_i . Therefore, the proposed scheme is secure against the denial of service attack.

6.7 Perfect forward secrecy

Perfect forward secrecy means that even if an adversary compromises all the passwords of the users, it still cannot compromise the session key. In the proposed scheme, the session key $SK = h(DID_i \parallel SID_j \parallel K_{ij} \parallel T_{ij})$ ($SK = h(DID_i \parallel SID_j \parallel K_{ji} \parallel T_{ji})$) is generated by three one-time random numbers u_i , r_i and r_j in each session. These one-time random numbers are only held by the user U_i and the server S_j , and cannot be retrieved from SK based on the security of CDH problem. Thus, even if an adversary obtains previous session keys, it cannot compromise other session key. Hence, the proposed scheme achieves perfect forward secrecy.

6.8 User's anonymity

In our proposed scheme, the user U_i 's login message is different in each login phase. Among each login message, $DID_i = u_i \cdot H(ID_i)$ is associated with a random number u_i which is known by U_i only. Therefore, any adversary cannot identify the real identity of the logon user and our scheme can provide the user's anonymity.

6.9 No verification table

In our proposed scheme, it is obvious that the user, the server and the registration center do not maintain any verification table.

6.10 Local password verification

In the proposed scheme, smart card checks the validity of user U_i 's identity ID_i and password pw_i before logging into server S_j . Since the adversary cannot compute the correct CID_i without the knowledge of ID_i and pw_i to pass the verification equation $H_i^* = H_i$, thus our scheme can avoid the unauthorized accessing by the local password verification.

6.11 Proper mutual authentication

In our scheme, the user first authenticates the server. U_i sends the message $\{DID_i, R_i\}$ to the server S_j to build an connection. After receiving the response message $\{W_j, R_j, Auth_{ji}\}$ sent from S_j , U_i computes T_{ij} , pub_j , K_{ij} , $Auth_{ij}$, and checks whether $Auth_{ij} = Auth_{ji}$. If they are equal, S_j is authenticated by U_i . Otherwise, U_i stops to login onto this server. Since $Auth_{ji} = h(DID_i \parallel SID_j \parallel K_{ji} \parallel R_j)$ and $K_{ji} = s_j \cdot R_i$, an adversary A cannot compute the correct K_{ji} without the knowledge of value of s_j . Any fabricated message $\{W'_j, R'_j, Auth'_{ji}\}$ cannot pass the verification. Then U_i computes M_i , N_i , d_{ij} , B_i , and sends the message $\{M_i, B_i\}$ to S_j . After receiving the message $\{M_i, B_i\}$ sent from U_i , S_j computes d_{ji} and checks whether $e(M_i +$

Table 2: Computational cost comparison of our scheme and other schemes.

	Proposed scheme	Liao et al.'s scheme [27]	Tseng et al.'s scheme [26]
C1	$3TG_{mul}+TG_H+2T_h$	$3TG_{mul}+TG_H+T_h$	$2TG_{mul}+TG_H+T_h$
C2	$8TG_{mul}+TG_H+TG_{add}+5T_h$	$5TG_{mul}+TG_H+TG_{add}+5T_h$	$3TG_{mul}+2T_h$
C3	$2TG_e+4TG_{mul}+TG_{add}+2T_h$	$2TG_e+5TG_{mul}+TG_{add}+2T_h$	$2TG_e+TG_{mul}+TG_H+TG_{add}+T_h$

$d_{ji} \cdot DID_i, pub_{RC}) = e(B_i, P)$. If they are not equal, S_j terminates this session. Otherwise, U_i is authenticated. Since $B_i = (r_i + d_{ij}) \cdot N_i$, an adversary A cannot compute the correct B_i without the knowledge of values of u_i and r_i etc. Any fabricated message $\{M'_i, B'_i\}$ cannot pass the verification. Therefore, our proposed scheme can provide proper mutual authentication.

§7 Performance comparison and functionality analysis

In this section, we compares the performance and functionality of our proposed scheme with some previously schemes. To analyze the computation cost, some notations are defined as follows.

TG_e : The time of executing a bilinear map operation, $e : G_1 \times G_1 \rightarrow G_2$.

TG_{mul} : The time of executing point scalar multiplication on the group G_1 .

TG_H : The time of executing a map-to-point hash function $H(\cdot)$.

TG_{add} : The time of executing point addition on the group G_1 .

T_h : The time of executing a one-way hash function $h(\cdot)$.

Since the XOR operation and the modular multiplication operation require very few computations, it is usually negligible considering their computation cost.

Table 2 shows the performance comparisons of our proposed scheme and some other related protocols. We mainly focus on three computation costs including: C1, the total time of all operations executed in the user registration phase; C2, the total time spent by the user during the process of login phase and verification phase; C3, the total time spent by the server during the process of verification phase. As shown in Table 2, Tseng et al.'s scheme are more efficient in terms of computation cost. However, Tseng et al.'s scheme is vulnerable to stolen smart card and offline dictionary attacks, server spoofing attack and insider attack, and cannot provide perfect forward secrecy, user's anonymity, proper mutual authentication and session key agreement. In our proposed scheme, the total computation cost of the user (C2) is $9TG_{mul}+TG_H+TG_{add}+5T_h$. But similar to that in Liao et al.'s scheme, the user U_i can pre-compute $R_i = r_i \cdot P$ in the client, and then the computation cost of the user (C2) requires $8TG_{mul}+TG_H+TG_{add}+5T_h$ on-line computation. It can be found that our proposed scheme spends a little more computation cost than Liao et al.'s scheme in C2, and the others are almost equal. However, Liao et al.'s scheme is vulnerable to stolen smart card and offline dictionary attacks and denial of service attack, and cannot provide user's anonymity and local password verification.

Table 3: Functionality comparisons among related multi-server authentication protocols.

	Proposed scheme	Liao et al. [27]	Tseng et al. [26]	Li et al. [20]	Lee et al. [18]	Shao et al. [17]	Lee et al. [19]
Resist stolen smart card and offline dictionary attacks	Yes	No	No	No	No	No	No
Resist replay attack	Yes	Yes	Yes	No	No	No	No
Resist impersonation attack	Yes	Yes	Yes	No	No	No	No
Resist server spoofing attack	Yes	Yes	No	No	No	No	No
Resist insider attack	Yes	Yes	No	Yes	Yes	No	Yes
Resist denial of service attack	Yes	No	Yes	Yes	Yes	Yes	No
Perfect forward secrecy	Yes	Yes	No	Yes	Yes	No	No
User's anonymity	Yes	No	No	Yes	Yes	No	Yes
No verification table	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local password verification	Yes	No	Yes	Yes	Yes	Yes	No
Proper mutual authentication	Yes	Yes	No	Yes	No	Yes	Yes

Table 3 lists the functionality comparisons among our proposed scheme and other related schemes. It is obviously that our scheme has many excellent features and is more secure than other related schemes.

§8 Conclusion

In this paper, we point out that Li et al.'s scheme is vulnerable to stolen smart card and offline dictionary attack, replay attack, impersonation attack and server spoofing attack. Furthermore, by analyzing some other similar schemes, we find the certain type of dynamic ID based and non-RC depended multi-server authentication scheme in which only hash functions are used is hard to provide perfect efficient and secure authentication. To compensate for these shortcomings, we improve the Liao et al.'s multi-server authentication scheme which is based on pairing and self-certified public keys, and propose a novel dynamic ID based and non-RC depended remote user authentication scheme for multi-server environments. The security and performance analyses show the proposed scheme is secure against various attacks and has many excellent features.

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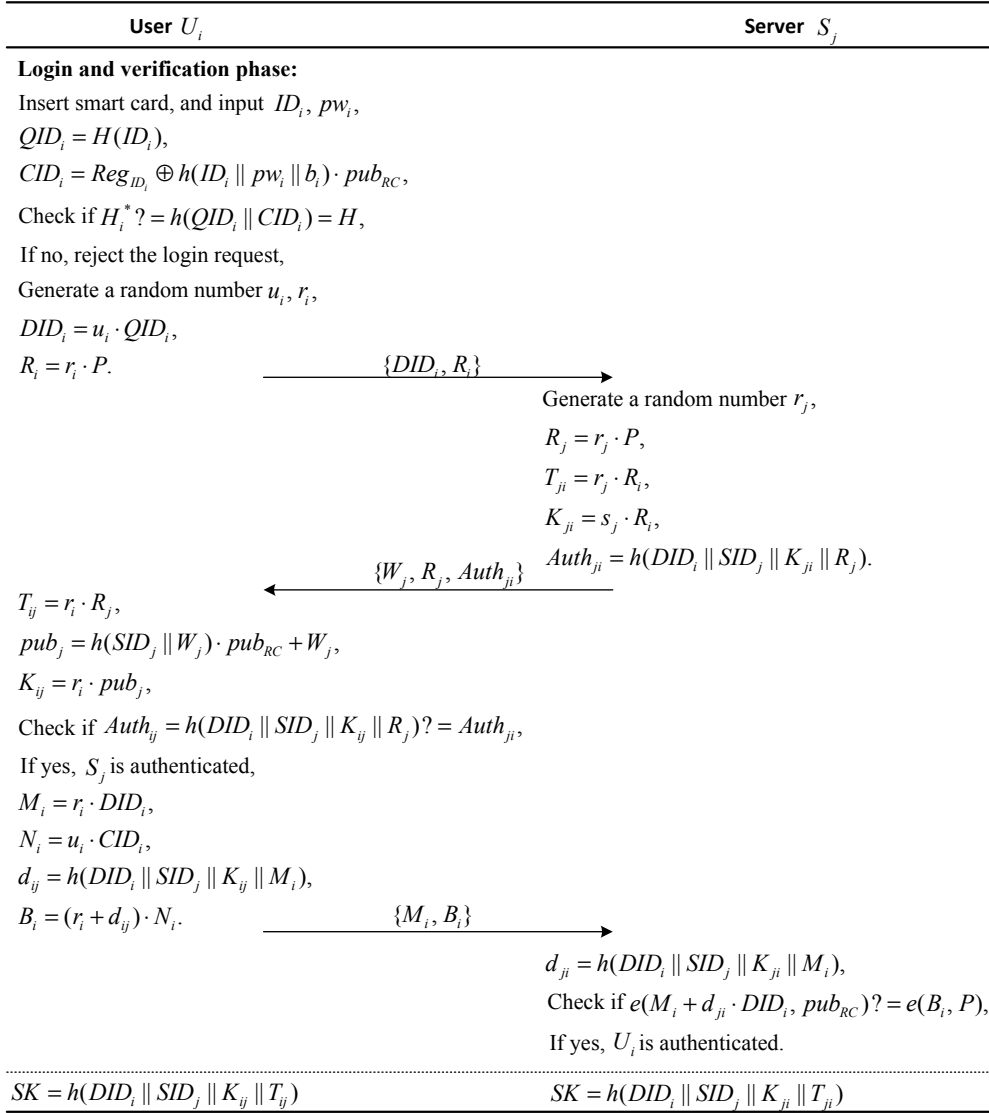


Figure 2: Login and verification phase of the proposed scheme.

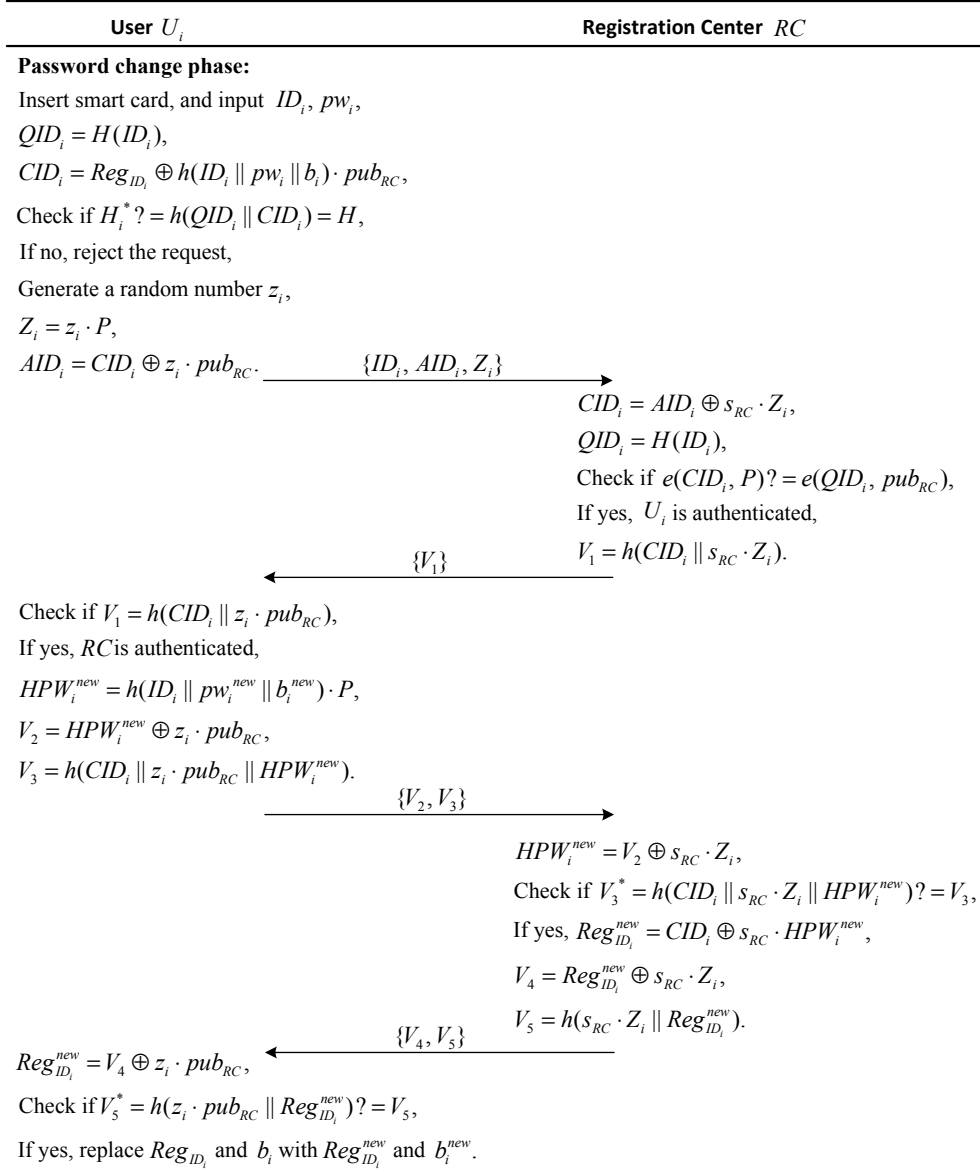


Figure 3: Password change phase of the proposed scheme.