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# Remote mutual authentication and key agreement scheme based on elliptic curve cryptosystem

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**Abstract**

*Remote mutual authentication is an important part of security, along with confidentiality and integrity, for systems that allow remote access over untrustworthy networks, like the Internet. In 2006, Shieh-Wang pointed out the weakness of Juang's remote mutual authentication scheme using smart card and further proposed a novel remote user authentication scheme using smart card. However, this paper demonstrates that Shieh-Wang's scheme still does not provide perfect forward secrecy and is vulnerable to a privileged insider's attack. We also present an improved scheme based on the Elliptic Curve Diffie-Hellman problem (ECDHP) and secure one-way hash function, in order to isolate such security problems.*

**Key Words:** *Authentication, password, key agreement, cryptanalysis, smart card, elliptic curve cryptosystem*

## 1. Introduction

Remote mutual authentication is a mechanism for two communicating parties to mutually authenticate each other through an insecure communication channel. In addition, a smart card based remote mutual authentication scheme is very practical to authenticate remote users [1, 2]. Since Lamport [3] proposed a remote authentication scheme in 1981, many researchers have proposed new schemes to improve the efficiency and security [4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

In 2000, Sun [4] proposed a cost effective unilateral remote authentication scheme in which only a server can authenticate a user's legitimacy. In 2002, Chien-Jan-Tseng [5] proposed an efficient remote mutual authentication scheme using smart card allowing server and user to authenticate each other. The advantages in the scheme include freely chosen passwords, no verification tables, low communication and computation costs. However, as demonstrated by Hsu [6], Chien-Jan-Tseng's scheme is vulnerable to the parallel session attack. Thereafter, in 2004, Juang [7] proposed another improved scheme preserving all the advantages of Chien-Jan-Tseng's scheme. Unlike Chien-Jan-Tseng's scheme, Juang's scheme is a nonce based authentication and key agreement scheme. Therefore, no synchronized clocks are required in the scheme. In addition, Juang's scheme generates a session key for the user and server in their subsequent communication.

Recently, Shieh-Wang [8], however, pointed out another weakness of Juang's scheme and then proposed an improvement of the scheme to improve the weakness. Shieh-Wang claimed that their scheme not only preserves all the advantages of Juang's scheme but also improves its efficiency.

Nevertheless, this paper demonstrates that Shieh-Wang's scheme still does not provide perfect forward secrecy [14] and is vulnerable to a privileged insider's attack [15, 16]. We also present an improved scheme based on Elliptic Curve Diffie-Hellman problem (ECDHP) and secure one-way hash function, in order to isolate such security problems. The Elliptic Curve cryptosystems [17, 18], which are based on the Elliptic Curve Discrete Logarithm Problem (ECDLP) over a finite field, have some advantages over other cryptosystems: The key size can be much smaller than those of the other cryptosystems since only exponential-time attacks have been known to occur so far, if the curve is carefully chosen [19], and that the Elliptic Curve Discrete Logarithms might still be intractable even if factoring and the multiplicative group discrete logarithm turn out to be tractable problems. As a result, the improved scheme has the following merits: (1) The scheme provides not only perfect forward secrecy but also explicit mutual authentication between the user and a remote server. (2) The scheme does not require time synchronization or a delay-time limitations by using timestamp between the user and the remote system. (3) In order to prevent the problems of clock synchronization or a delay-time limitations, the proposed scheme adopts a nonce-based scheme [20] instead of a timestamp-based scheme. (4) The security of the proposed scheme is based on Elliptic Curve Diffie-Hellman problem (ECDHP) [21] and one-way hash function to suitable for light-weight authentication and key agreement. (5) The scheme resists the privileged insider's attack. (6) The scheme provides secure password change scheme without helping of the remote server.

The remainder of this paper is organized as follows¿ Section 2 briefly reviews Shieh-Wang's scheme. Section 3 demonstrates the security weaknesses of Shieh-Wang's scheme. The proposed authentication scheme is presented in Section 4, while Sections 5 and 6 discusses the security and performance of the proposed scheme, respectively. The conclusion is given in Section 7.

## 2. Review of Shieh-Wang's scheme

This section briefly reviews Shieh-Wang's a remote mutual authentication and key agreement scheme using smart card with secure one-way hash function [8]. Some of the notations used in this paper are defined as follows.

- $U_i$: user $i$
- $ID_i$: identity of $U_i$
- $PW_i$: password of $U_i$
- $x$: the secret key maintained by the server
- $h(\cdot)$: a secure one-way hash function
- $\oplus$: exclusive-or operation
- $||$: string concatenation operation
- $q$: the order of the underlying finite field $F_q$

- $E$: a suitably chosen Elliptic Curve defined over $F_q$
- $P$: a base point in the generator point $E$
- $n$: the prime order of $P$
- $O$: the point at infinity, where $nP = O$ and $P \neq O$ .

Figure 1 shows Shieh-Wang's scheme and the scheme consists of two phases: the registration, and the login and key agreement.

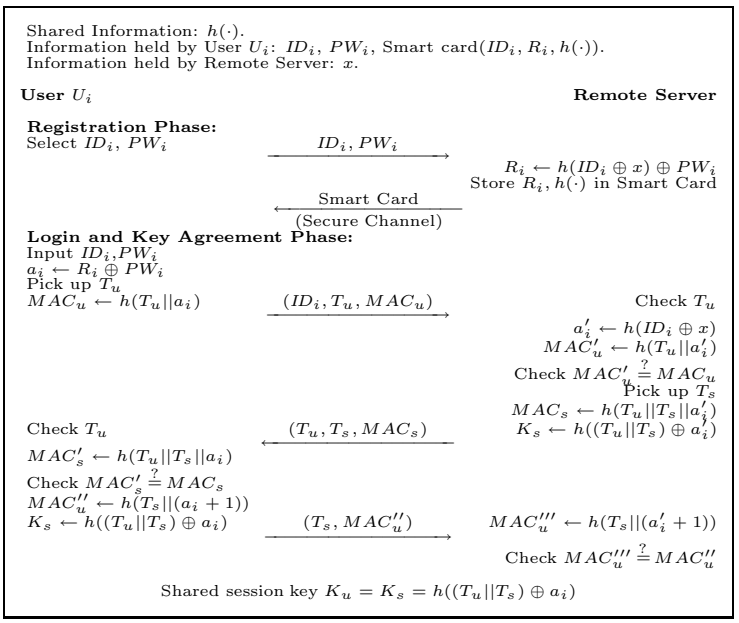


**Figure 1**. Shieh-Wang's remote mutual authentication and key agreement scheme.

## 2.1. Registration phase

Assume a user $U_i$ submits his/her identity $ID_i$ and password $PW_i$ to the server over a secure channel for registration. If the request is accepted, the server computes $R_i = h(ID_i \oplus x) \oplus PW_i$ and issues $U_i$ a smart card containing $R_i$ and $h(\cdot)$.

## 2.2. Login and key agreement phase

When the user $U_i$ wants to login to the server, he/she first inserts his/her smart card into a card reader then inputs his/her identity $ID_i$ and password $PW_i$. The smart card then performs the following steps to begin an access session:

1. Compute $a_i = R_i \oplus PW_i$.
2. Acquire current time stamp $T_u$, store $T_u$ temporarily until the end of the session, and compute $MAC_u = h(T_u||a_i)$.

3. Send the message $(ID_i, T_u, MAC_u)$ to the server and wait for response from the server. If no response is received in time or the response is incorrect, report login failure to the user and stop the session.

After receiving the message $(ID_i, T_u, MAC_u)$ from $U_i$, the server performs the following steps to assure the integrity of the message, respond to $U_i$, and challenge $U_i$ to avoid replay:

1. Check the freshness of $T_u$. If $T_u$ has already appeared in a current executing session of user $U_i$, reject $U_i$'s login request and stop the session. Otherwise, $T_u$ is fresh.

2. Compute $a'_i = h(ID_i \oplus x)$, $MAC'_u = h(T_u||a'_i)$, and check whether $MAC'_u$ is equal to the received $MAC_u$. If it is not, reject $U_i$'s login and stop the session.

3. Acquire the current time stamp $T_s$. Store temporarily paired time stamps $(T_u, T_s)$ and $ID_i$ for freshness checking until the end of the session. Compute $MAC_s = h(T_u||T_s||a'_i)$ and session key $K_s = h((T_u||T_s) \oplus a'_i)$. Then, send the message $(T_u, T_s, MAC_s)$ back to $U_i$ and wait for response from $U_i$. If no response is received in time or the response is incorrect, reject $U_i$'s login and stop the session.

On receiving the message $(T_u, T_s, MAC_s)$ from the server, the smart card performs the following steps to authenticate the server, achieve session key agreement, and respond to the server:

1. Check if the received $T_u$ is equal to the stored $T_u$ to assure the freshness of the received message. If it is not, report login failure to the user and stop the session.

2. Compute $MAC'_s = h(T_u||T_s||a_i)$ and check whether it is equal to the received $MAC_s$. If not, report login failure to the user and stop. Otherwise, conclude that the responding party is the real server.

3. Compute $MAC''_u = h(T_s||(a_i + 1))$ and session key $K_s = h((T_u||T_s) \oplus a_i)$, then send the message $(T_s, MAC''_u)$ back to the server. Note that, in the message $(T_s, MAC''_u)$, $T_s$ is a response to the server.

When the message $(T_s, MAC''_u)$ from $U_i$ is received, the server performs the following steps to authenticate $U_i$ and achieve key agreement:

1. Check if the received $T_s$ is equal to the stored $T_s$. If it fails, reject $U_i$'s login request and stop the session.

2. Compute $MAC'''_u = h(T_s||(a'_i + 1))$ and check whether it is equal to $MAC''_u$. If it is not, reject $U_i$'s login request and stop the session. Otherwise, conclude that $U_i$ is a legal user and permit the user $U_i$'s login. At this moment, mutual authentication and session key agreement between $U_i$ and the server are achieved. From now on, the user $U_i$ and the server can use the session key $K_s$ in their further secure communication until the end of the access session.

## 3. Weaknesses of Shieh-Wang's scheme

This section shows that Shieh-Wang's remote mutual authentication and key agreement scheme does not provide perfect forward secrecy [14] and is vulnerable to a privileged insider attack [15, 16]. In addition, the scheme has a time synchronization problem [7].

### 3.1. Perfect forward secrecy problem

Perfect forward secrecy [14] is a very important security requirement for evaluating a strong protocol. A protocol with perfect forward secrecy assures that even if one entity's long-term key (e.g. user password or server's secret key) is compromised, it will never reveal any old fresh session keys used before. For example, the well-known Diffie-Hellman key agreement scheme can provide perfect forward secrecy.

However, Shieh-Wang's scheme does not provide it because once the secret key $x$ of the server is disclosed, all previous fresh session keys $K_s$ will also be opened and hence previous communication messages will be learned. In the Shieh-Wang's scheme, suppose an attacker $E$ obtains the secret key $x$ from the compromised server and intercepts transmitted values ($ID_i$, $T_u$, $T_s$), from an open network. It is easy to obtain the information since its are exposed over an open network. Then, $E$ can easily compute $a_i = h(ID_i \oplus x)$ by using the obtained $ID_i$. Finally, $E$ can compute the shared session key $K_s = h((T_u||T_s) \oplus a_i)$ by using $a_i$, $T_u$ and $T_s$. By using the $K_s$, $E$ can eavesdrop all previous communication messages. Obviously, Shieh-Wang's scheme does not provide perfect forward secrecy.

### 3.2. Privileged insider's attack

In practice, a user uses the same password to access several servers for his/her convenience. In the registration phase of Shieh-Wang's scheme, $U_i$'s password $PW_i$ will be revealed to the remote server because it is transmitted directly to the server. Then, the privileged insider of the remote server may try to use $PW_i$ to impersonate $U_i$ to login the other servers that $U_i$ has registered with outside this system [15]. If the targeted outside server adopts the normal password authentication scheme, it is possible that the privileged insider of the server can successfully impersonate $U_i$ to login it by using $PW_i$. Although, it is also possible that all the privileged insiders of the server are trusted and $U_i$ does not use the same password to access several servers, the implementers and the users of the scheme should be aware of such a potential weakness. Obviously, Shieh-Wang's scheme is vulnerable to a privileged insider attack.

### 3.3. Time synchronization problem

The schemes based on timestamps must overcome the problems of clock synchronization and delay-time limitation so that we better implement them in fast local area networks. Because Shieh-Wang's scheme also used timestamps to resist replay attacks, the scheme can lead to serious clock synchronization problems, namely that the user's time and the server's time must differ only in a small range [7]. For example, in a large-scale network, it is almost impossible to maintain the synchronization of clocks among all entities in the network and to guarantee the delay time of transmission. Therefore, we proposed a nonce-based and simplified scheme to avoid these clock synchronization and delay-time limitation problems.

## 4. Proposed scheme

This section proposes an improvement of Shieh-Wang's scheme so that they can withstand the above mentioned problems. The proposed scheme consists of three phases: the registration, the login and key agreement, and the password change. Figure 2 shows the proposed remote mutual authentication and key agreement scheme. It works as follows.

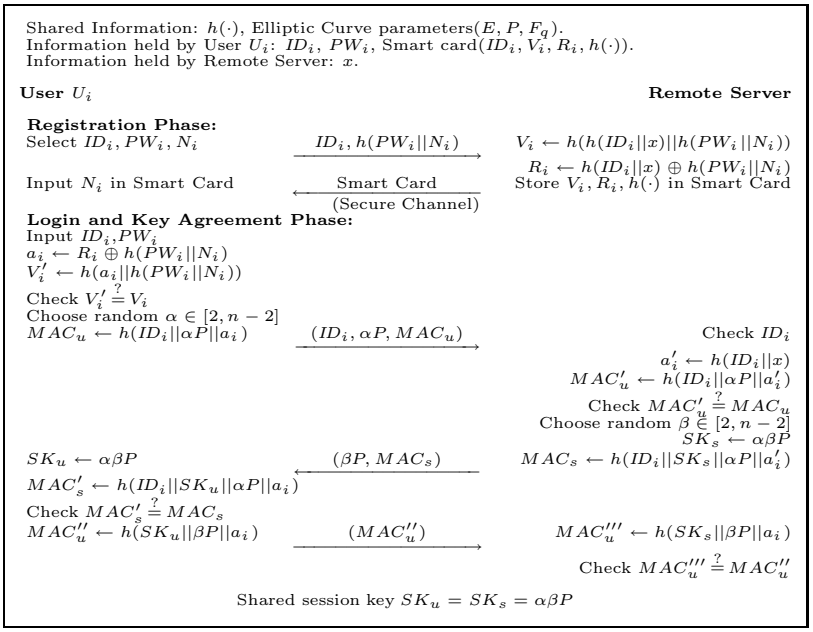


**Figure 2**. Proposed remote mutual authentication and key agreement scheme.

## 4.1. Registration phase

When a new user $U_i$ wants to registration, the proposed registration phase performs the following steps:

1. $U_i$ freely chooses his/her identity $ID_i$, password $PW_i$ and a random number $N_i$. Then, $U_i$ computes $h(PW_i||N_i)$ and submits it with $ID_i$ to the remote server for registration. These private data must be sent in person or over a secure channel.

2. If the request is accepted, the server computes $V_i = h(h(ID_i||x)||h(PW_i||N_i))$ and $R_i = h(ID_i||x) \oplus h(PW_i||N_i)$, and issues $U_i$ a smart card containing $V_i$, $R_i$ and $h(\cdot)$.

3. After receiving the smart card, $U_i$ enters $N_i$ into his/her smart card.

## 4.2. Login and key agreement phase

When the user $U_i$ wants to login to the server, he/she first inserts his/her smart card into a card reader then inputs his/her identity $ID_i$ and password $PW_i$. The smart card then performs the following steps to begin an access session:

1. Compute $a_i = R_i \oplus h(PW_i||N_i)$.

2. Compute $V_i' = h(a_i||h(PW_i||N_i))$ and check whether it is equal to the stored $V_i$. If not, report password $PW_i$ is incorrect to the user. This verification process performs only three times that can withstand password guessing attack by using the stolen or lost smart card.

3. Choose a random number $\alpha \in [2, n-2]$, and compute $\alpha P$ and $MAC_u = h(ID_i||\alpha P||a_i)$.

4. Send the message $(ID_i, \alpha P, MAC_u)$ to the server.

After receiving the message $(ID_i, \alpha P, MAC_u)$ from $U_i$, the server performs the following steps to assure the integrity of the message, respond to $U_i$, and challenge $U_i$ to avoid replay:

1. Check the correctness of $ID_i$. If it is incorrect, reject $U_i$'s login request and stop the session.
2. Compute $a_i' = h(ID_i||x)$, $MAC_u' = h(ID_i||\alpha P||a_i')$, and check whether $MAC_u'$ is equal to the received $MAC_u$. If it is not, reject $U_i$'s login and stop the session.
3. Choose a random number $\beta \in [2, n-2]$, compute $\beta P$, session key $SK_s = \alpha\beta P$ and $MAC_s = h(ID_i||SK_s||\alpha P||a_i')$. Then, send the message $(\beta P, MAC_s)$ back to $U_i$ and wait for response from $U_i$.

On receiving the message $(\beta P, MAC_s)$ from the server, the smart card of $U_i$ performs the following steps to authenticate the server, achieve session key agreement, and respond to the server:

1. Compute session key $SK_u = \alpha\beta P$ and $MAC_s' = h(ID_i||SK_u||\alpha P||a_i)$, and check whether it is equal to the received $MAC_s$. If not, report login failure to the user and stop. Otherwise, conclude that the responding party is the real server.
2. Compute $MAC_u'' = h(SK_u||\beta P||a_i)$ and send the message $(MAC_u'')$ back to the server. Note that, in the message $(MAC_u'')$ is a response to the server.

When the message $(MAC_u'')$ from $U_i$ is received, the server performs the following steps to authenticate $U_i$ and achieve key agreement:

1. Compute $MAC_u''' = h(SK_s||\beta P||a_i')$.
2. Check whether $MAC_u'''$ is equal to $MAC_u''$. If it is not, reject $U_i$'s login request and stop the session. Otherwise, conclude that $U_i$ is a legal user and permit the user $U_i$'s login. At this moment, mutual authentication and session key agreement between $U_i$ and the server are achieved. From now on, the user $U_i$ and the server can use the session key $SK_u = SK_s = \alpha\beta P$ in their further secure communication until the end of the access session.

## 4.3. Password change scheme

The password change scheme is invoked whenever a user $U_i$ wants to change his password $PW_i$. By invoking this scheme, $U_i$ can easily change his password without taking any assistance from the remote server. Figure 3 shows the proposed password change scheme and it works as follows.

1. $U_i$ inserts his/her smart card into a card reader then inputs his/her identity $ID_i$ and password $PW_i$.
2. The smart card computes $a_i = R_i \oplus h(PW_i||N_i)$.
3. The smart card computes hash value $V_i' = h(a_i||h(PW_i||N_i))$ and verifies it with stored $V_i$. If it holds, the smart card proceeds to the next step; otherwise, terminates the operation. This verification process performs only three times that can withstand password guessing attack by using stolen or lost smart card.

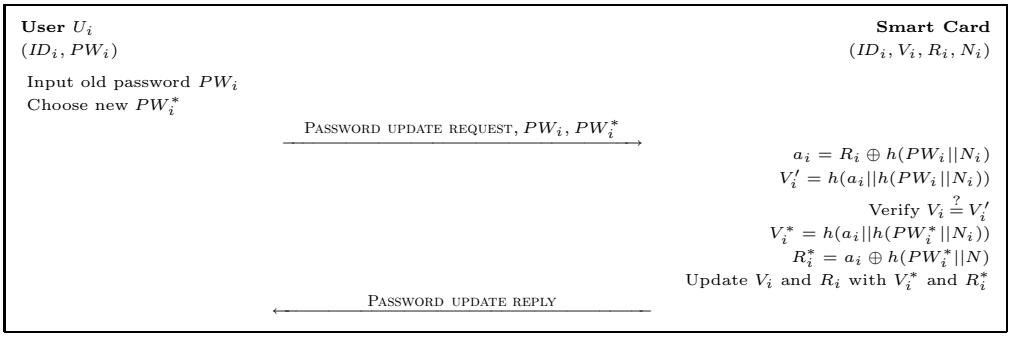


**Figure 3**. Password change scheme.

4. $U_i$ submits a new password $PW_i^*$.

5. The smart card computes $V_i^* = h(a_i||h(PW_i^*||N_i))$ and $R_i^* = a_i \oplus h(PW_i^*||N)$.

6. The password has been changed now with the new password $PW_i^*$ and the smart card replaced the previously stored $V_i$ and $R_i$ values by $V_i^*$ and $R_i^*$ values.

# 5. Security analysis

This section analyzes the security of the proposed remote mutual authentication and key agreement scheme. First, we define the security terms [14, 17, 18, 23, 24, 25] needed to conduct an analysis of the proposed scheme. They are as follows.

**Definition 1** *A weak secret key (user's password $PW_i$) is the value of low entropy $W(k)$, which can be guessed in polynomial time.*

**Definition 2** *A strong secret key (server's secret key $x$) is the value of high entropy $S(k)$, which cannot be guessed in polynomial time.*

**Definition 3** *The Elliptic Curve Discrete Logarithm Problem ($ECDLP$) is as follows: given a public key point $V = \alpha P$, it is hard to compute the secret key $\alpha$.*

**Definition 4** *The Elliptic Curve Diffie-Hellman Problem ($ECDHP$) is as follows: given point elements $\alpha P$ and $\beta P$, it is hard to find $\alpha\beta P$.*

**Definition 5** *A secure one-way hash function $y = h(x)$ is one where given $x$ to compute $y$ is easy, and given $y$ to compute $x$ is hard.*

The following eight security properties [14, 22, 24] must be considered for the proposed protocol: a replay attack,a guessing attack, a reflection and parallel session attack, a privileged insider attack, a mutual authentication, a perfect forward secrecy, a fast wrong password detection and a secure password change. Regarding the above mentioned definitions, the followings are used to analyze the eight security properties of the proposed scheme.

1. *The proposed scheme can resist a replay attack:* When the server receives the message $(ID_i, \alpha P,\ MAC_u)$, it includes a fresh Diffie-Hellman element $\alpha P$ from $U_i$. Therefore, the server must send back the received $T$ to $U_i$ including $MAC_s$ as a response. When $U_i$ receives the message $(\beta P, MAC_s)$, it includes the fresh Diffie-Hellman element $\alpha P$ in the $MAC_s$. Note that $\alpha P$ is fresh on each session. Besides, $MAC_u$ and $MAC_s$ guarantee their integrity and source, respectively. In addition, it is impossible to create corresponding responses and their message authentication codes, $MAC_s$ and $MAC''_u$, without knowing the shared secret value $a_i$ between $U_i$ and the server. Therefore, except for $U_i$ and the server, no one can pass the challenges.

2. *The proposed scheme can resist a guessing attack:* Assume a user lost his/her smart card and it is found by an attacker or an attacker steals a user's smart card. The attacker, however, cannot impersonate a legitimate user $U_i$ by using the smart card because no one can reveal the $PW_i$ from value $R_i$ in the smart card without knowing the system's secret key $x$. Furthermore, the server's secret key $x$ is protected by the secure one-way hash function $h(\cdot)$. It is computationally infeasible to derive $x$ from the value $h(ID_i||x)$. In the same way, the shared secret $a_i$ between $U_i$ and the server cannot be derived from the message authentication code $MAC_u$, $MAC_s$, or $MAC''_u$. Therefore, $a_i$ is safely shared only between $U_i$ and the server.

3. *The proposed scheme can resist a reflection attack and a parallel session attack [6]:* In the proposed scheme, the reflection attack and a parallel session attack will fail because of the asymmetric structure of the message authentication codes $MAC_u$ and $MAC''_u$. Note that $MAC_u \leftarrow h(T||\alpha P||a_i)$ and $MAC''_u \leftarrow h(SK_u||\beta P||a_i)$. Therefore, the proposed scheme can resist a reflection attack and a parallel session attack.

4. *The proposed scheme can resist a privileged insider attack:* Since $U_i$ registers to the server by presenting $h(PW_i||N_i)$ instead of $PW_i$, the insider of the server cannot directly obtain $PW_i$ without knowing of random nonce $N_i$. Therefore, the proposed scheme can withstand the insider attack.

5. *The proposed scheme provides the mutual authentication:* Mutual authentication between $U_i$ and the server is achieved, because $U_i$ and the server authenticate each other with the message authentication codes $MAC_s$, and $MAC''_u$, respectively. Since nobody can create the correct message authentication codes without knowing the shared secret value $a_i$ between $U_i$ and the server, $a_i$ is used to confirm the legitimacy of each party. In other words, it is infeasible for an intruder or a pretended server to masquerade as a legal party. Also, the proposed scheme uses the Elliptic Curve Diffie-Hellman key exchange algorithm in order to provide mutual explicit key authentication. Then, the key is explicitly authenticated by a mutual confirmation session key, $SK = \alpha\beta P$.

6. *The proposed scheme provides a perfect forward secrecy:* In the proposed scheme, since the Elliptic Curve Diffie-Hellman key exchange algorithm is used to generate a session key $SK = \alpha\beta P$, perfect forward secrecy is ensured because an attacker with a compromised server's secret key $x$ is only able to obtain the $\alpha P$ and $\beta P$ from an earlier session. In addition, it is also computationally infeasible to obtain the session key $\alpha\beta P$ from $\alpha P$ and $\beta P$, as it is a ECDLP and a ECDHP.

7. *The proposed scheme provides a fast wrong password detection:* In Shieh-Wang's scheme, if user $U_i$ input a wrong password $PW_i$ by mistake, this wrong password will be detected by the remote server in the login and key agreement phase. Therefore, Shieh-Wang's scheme is slow to detect the user's wrong password.

In contrast to Shieh-Wang's scheme, in the proposed scheme, if user $U_i$ inputs the wrong password by mistake, this wrong password will be quickly detected by a smart card since the smart card can verify $V_i' = V_i$ using the stored $K_i$ in step 2 of the login and key agreement phase. Therefore, the proposed scheme provides fast wrong password detection.

8. *The proposed scheme provides a secure password change:* Shieh-Wang's scheme does not provide password change scheme. The proposed password change scheme is simple and secure. Because the smart card can verify $V_i^*$ using the stored $V_i$ in step 3 of the password change scheme, when the smart card was lost or steal, unauthorized users cannot change the password of the card without knowing the $U_i$'s password $PW_i$. Therefore, the proposed password change scheme provides secure password change.

We compared the proposed scheme with other related schemes [9, 10, 11, 12, 13] as well as Shieh-Wang's scheme [8]. Table 1 shows the comparison results of the security properties of the proposed scheme and various other remote authentication schemes based on smart cards. As show in Table 1, in contrast to related schemes, the proposed scheme is more secure and practical for smart card-based remote mutual authentication and key agreement.

**Table 1**. Security properties of the proposed scheme with other related schemes.

| Security properties | Liaw et al. [9] | Cheng et al. [10] | Wang et al. [11] | Yang et al. [12] | Xu et al. [13] | Shieh-Wang [8] | Proposed scheme |
|---|---|---|---|---|---|---|---|
| Replay attack | Secure | Secure | Secure | Secure | Secure | Secure | Secure |
| Guessing attack | Secure | Insecure | Insecure | Secure | Secure | Secure | Secure |
| Reflection attack | Secure | Secure | Insecure | Secure | Secure | Secure | Secure |
| Parallel session attack | Secure | Insecure | Secure | Secure | Secure | Secure | Secure |
| Privileged insider attack | Insecure | Insecure | Secure | Secure | Insecure | Insecure | Secure |
| Mutual authentication | Provide | Provide | Provide | Provide | Provide | Provide | Provide |
| Explicit mutual authentication | No provide | No provide | No provide | No provide | No provide | No provide | Provide |
| Session key agreement | Provide | Provide | Provide | Provide | Provide | Provide | Provide |
| Perfect forward secrecy | Provide | No provide | No provide | Provide | No provide | No provide | Provide |
| Wrong password detection | Slow | Fast | Fast | Slow | Slow | Slow | Fast |
| Secure password change | No provide | Provide | Provide | No provide | No provide | No provide | Provide |
| Time synchronization | No required | Required | Required | No required | Required | No required | No required |
| No verification table | Yes | No | Yes | Yes | Yes | Yes | Yes |

## 6. Performance comparisons

This section analyzes the efficiency of the proposed scheme. Table 2 provides computational costs of the proposed scheme with various other related schemes [9, 10, 11, 12, 13] as well as Shieh-Wang's scheme [8] in regards to the registration, login, authentication and key agreement, and password change phases.

In the registration phase, the 3 time one-way function operation and 1 time exclusive-OR operation are required to resist an insider attack. In the authentication and key agreement phase, the 4 times modular addition operations and 6 times one-way function operations are required to provide session key agreement and perfect forward secrecy. In the password change phase, the 4 time one-way function operations and 2 time exclusive-OR operations are required to resist a stolen or lost smart card attack. The symmetric key computations and hash functions are faster than the asymmetric key computations.

**Table 2**. Computational costs of the proposed scheme with other related schemes.

| | Registration phase | Login phase | Authentication and key agreement phase | Password change phase |
|---|---|---|---|---|
| Proposed scheme | $3T(f)$ $1T(\oplus)$ | $3T(f)$ $1T(\oplus)$ | $4T(MA)$ $6T(f)$ | $4T(f)$ $2T(\oplus)$ |
| Shieh-Wang's scheme [8] | $1T(f)$ $1T(\oplus)$ | $1T(f)$ $1T(\oplus)$ | $8T(f)$ $3T(\oplus)$ | No support |
| Liaw et al.'s scheme [9] | $1T(f)$ $1T(\oplus)$ | $1T(f)$ $1T(\oplus)$ | $4T(ME)$ $2T(f)$ $6T(S)$ $2T(\oplus)$ | $2T(\oplus)$ |
| Cheng et al.'s scheme [10] | $2T(f)$ $1T(\oplus)$ | $(n+1)T(f)$ $2T(\oplus)$ | $(n+3)T(f)$ $3T(\oplus)$ | $3T(f)$ $5T(\oplus)$ |
| Wang et al.'s scheme [11] | $3T(f)$ $3T(\oplus)$ | $4T(f)$ $5T(\oplus)$ | $4T(f)$ $5T(\oplus)$ | $4T(f)$ $4T(\oplus)$ |
| Yang et al.'s scheme [12] | $5T(f)$ $3T(\oplus)$ | $1T(f)$ $1T(\oplus)$ $1T(ME)$ | $3T(ME)$ $4T(A)$ | $2T(f)$ $2T(\oplus)$ |
| Xu et al.'s scheme [13] | $1T(ME)$ $2T(f)$ $1T(\oplus)$ | $2T(ME)$ $3T(f)$ $1T(\oplus)$ | $4T(ME)$ $6T(f)$ | No support |

$T(f)$: computation cost of one-way function; $T(\oplus)$: computation cost of exclusive-OR operation or addition operation; $T(S)$: computation cost of symmetric encryption; $T(A)$: computation cost of asymmetric encryption; $T(MA)$: computation cost of modular addition; $T(ME)$: computation cost of modular exponentiation.

On a typical workstation, the asymmetric key computations can be performed 2 times per second, symmetric key computations can be performed 2,000 times per second and hash function can be performed 20,000 times per second. To provide the computational efficiency, we can change the the Diffie-Hellman key exchange algorithm with nonce-based key exchange algorithm in the proposed scheme. In this case, the proposed scheme cannot provide the perfect forward secrecy. But, the computation costs are very low because only a few hashing function computations are needed like other related schemes.

In addition, other security requirements including session key agreement can still be satisfied unlike other related schemes. Therefore, as in Tables 1 and 2, we can see that the proposed scheme not only is secure to various cryptographic attacks, but also has the reasonable computational costs.

# 7. Conclusion

This paper demonstrated that Shieh-Wang's scheme does not provide perfect forward secrecy and is vulnerable to a privileged insider's attack, and then an improved scheme based on Elliptic Curve Diffie-Hellman problem and one-way hash function was presented in order to resolve such problems. As a result, in contrast to Shieh-Wang's scheme, the proposed scheme is able to provide greater security and practicality.

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