An Improved Lightweight Two-Factor Authentication and Key Agreement Protocol with Dynamic Identity Based on Elliptic Curve Cryptography

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Abstract

With the rapid development of the Internet of Things, the problem of privacy protection has been paid great attention. Recently, Nikooghadam et al. pointed out that Kumari et al.’s protocol can neither resist off-line guessing attack nor preserve user anonymity. Moreover, the authors also proposed an authentication supportive session initial protocol, claiming to resist various vulnerability attacks. Unfortunately, this paper proves that the authentication protocols of Kumari et al. and Nikooghadam et al. have neither the ability to preserve perfect forward secrecy nor the ability to resist key-compromise impersonation attack. In order to remedy such flaws in their protocols, we design a lightweight authentication protocol using elliptic curve cryptography. By way of informal security analysis, it is shown that the proposed protocol can both resist a variety of attacks and provide more security. Afterward, it is also proved that the protocol is resistant against active and passive attacks under Dolev-Yao model by means of Burrows-Abadi-Needham logic (BAN-Logic), and fulfills mutual authentication using Automated Validation of Internet Security Protocols and Applications (AVISPA) software. Subsequently, we compare the protocol with the related scheme in terms of computational complexity and security. The comparative analytics witness that the proposed protocol is more suitable for practical application scenarios.

Keywords: Elliptic curve cryptography, Two-factor, Authentication, AVISPA, BAN-Logic

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1. Introduction

With the growing applications of cloud computing and multimedia services, the issue of communication privacy protection has gained more attention. To solve the privacy problem, numerous authentication and key agreement protocols are presented [1-20]. In order to login the server, the users execute the authentication process through session initial protocol (SIP). More precisely, SIP is a communication protocol that signals and controls multimedia communication sessions in practical applications, such as telecare medical information systems, distributed cloud computing environment, and internet telephony etc. Authentication and key agreement is a vital part of SIP. After the first authentication protocol was presented by Franks et al. in 1999 [21], many researchers analyzed and designed a lot of authentication and key agreement protocols based on the work of Franks et al. However, most of these schemes have at least one security vulnerability, such as perfect forward secrecy and off-line password guessing attack, etc [22-25].

1.1 Related Work

Recently, Chang et al. [26] observed that Wang et al.’s protocol [27] is unable to resist impersonation attack and provides user-untraceability because the identity is transmitted in login request message. Moreover, Chang et al. [26] also pointed out that password changing phase has no verification step in Wang et al.’s protocol [27]. Implying that the legitimate user will not be able to access the remote server anymore. In order to solve these problems, Chang et al. [26] presented a dynamic-identity based remote user authentication scheme while only incorporating hash function without session key agreement. In 2014, Kumari et al. [28] revealed that Chang et al. [26] protocol cannot resist off-line password guessing attack, impersonation attacks, etc. Further, Chang et al. [26] protocol also faces denial of service and cannot provide session key. For eliminating these vulnerabilities in Chang et al. protocol [26], Kumari et al. [28] also designed an authentication protocol. However, Chaudhry et al.[29] identified that Kumari et al.’s protocol [28] is still vulnerable against smart card stolen attack and cannot provide user anonymity in 2015. Subsequently, Chaudhry et al. [29] proposed an improved remote user authentication scheme with privacy preserving to remedy those flaws of Kumari et al.’s protocol [28]. But in 2016, Nikooghadam et al. [30] proved that Kumari et al. [28]’s and Chaudhry et al. [29]’s protocols are unable to resist offline-password-guessing attacks. Afterward, Nikooghadam et al. [30] designed a new authentication protocol and asserted that their protocol can both resist various attacks and provide user-anonymity. But, we remark that Nikooghadam et al.’s protocol [30] also has some flaws including perfect forward secrecy and off-line password guessing attack, etc. In fact, in throughout aforementioned protocols, the authors only used one-way hash function to provide security. Moreover, there exist several defects in the designs of authentication protocols. Under these circumstances, it is impossible to preserve perfect-forward-secrecy and avoid some known attacks, such as impersonation attacks and off-line password guessing attack, etc. In order to establish secure shared key in an authentication scheme, public key cryptography, which can efficiently provide perfect-forward-secrecy and resist various known attacks according to [47-52], is considered as the first choice including elliptic curve cryptography (ECC), RSA, etc. Because, the elliptic curve cryptography is more efficient than RSA under the same security condition, therefore, it is widely used in many special scenarios, especially for resource-constrained devices.
1.2 Contributions and Organization

In order to fill the aforementioned gaps, we present an improved authentication protocol with a full security function. The contributions of this paper are following:

(1) We present a supplementary cryptanalysis of Kumari et al.’s protocol and point out that it is still vulnerable to key-compromise impersonation attack and is unable to provide perfect-forward-secrecy. Moreover, we also remark that Nikooghadam et al.’s protocol is unable to provide perfect forward secrecy and is also vulnerable to off-line password guessing attack and key-compromise impersonation attack.

(2) We establish a novel lightweight authentication protocol for SIP using ECC.

(3) By heuristic security analysis, we illustrate that the proposed protocol is immune to all known attacks. Moreover, the proposed protocol can provide more comprehensive security functions including perfect forward secrecy, dynamic identity, and anonymity, etc.

(4) Via AVISPA software simulation verification, we show that the improved protocol is SAFE against active and passive attacks including replay and man-in-the-middle attacks under the Dolev-Yao model[31].

(5) According to BAN-Logic proof, we show that user and server can mutual authenticate successfully each other in the improved protocol.

(6) Comparing with the relevant solutions, we remark that our protocol is more secure and suitable for application in the actual scene.

The rest of this paper is organized as follows: attacker model and intractable problems are listed in Section 2. The protocol of Kumari et al. and its cryptanalysis is explained in Section 3. The protocol of Nikooghadam et al. and its cryptanalysis is provided in Section 4. The proposed scheme is presented in Section 5. The heuristic security analysis, simulation and security proof through AVISPA software and BAN-Logic are presented in Sections 6, 7 and 8, respectively. Security and performance comparisons are depicted in Section 9. Finally, the conclusion is summarised in Section 10.

2. Preliminaries

In this section, we introduce the capacities of the adversary of the authentication protocol. Some notations used in this paper are listed in Table 1.

2.1 Attacker model

According to [32–35], throughout this paper, we summarize the capacities of the attacker $\mathcal{A}$ suitable for the whole paper as follows:

(1) According to [33,34], if $\mathcal{A}$ steals the smart card of user or is in the effective range of the smart card being attacked, $\mathcal{A}$ may have the ability to obtain all datum stored in smart card by using the power-analysis technology.

(2) In open channels, all datum transmitted on these channels are public. So $\mathcal{A}$ has the capacity to eavesdrop, delete, modify, insert, replay, and block these messages on public channels.

(3) According to [32,35], $\mathcal{A}$ can have the ability to guess identity and password simultaneously in polynomial time. Thus, $\mathcal{A}$ can traverse all pairs of identity and password in dictionary space with in polynomial time.
According to [32,35], $\mathcal{A}$ can either steal password or get all datum from user’s smart card, but not both. If they are compromised by $\mathcal{A}$ simultaneously, then any two-factor authentication protocol is insecure.

When perfect forward secrecy [32,35] and key-compromise user impersonation attack are discussed, the long-term private key of the server can be leaked to $\mathcal{A}$. Since perfect forward security is the ultimate security, and key-compromise user impersonation attack is the ultimate attack, if an authentication protocol can both provide forward security and resist key-compromise user impersonation attack, it will be a better protocol. When assessing any attack, key-compromise user impersonation attack in particular, it is assumed that any adversary cannot get the verifiers and the private key of server simultaneously.

2.2 Intractable problems over ECC

Generally, let $p$ be a secure prime number and $F_p$ be a finite field, the elliptic curve equation in ECC is defined in the following form:

$$E_p(a,b): y^2 = x^3 + ax + b \pmod{p}$$

Where $a, b \in F_p$.

- **Elliptic curve discrete logarithm problem (ECDLP):** Let $P$ is a generator of $E_p(a,b)$ and $Q = xP$, where $x \in_R F_p$, it is almost impossible for $\mathcal{A}_{PPT}$ (probabilistic polynomial time adversary) to figure out the random number $x$ satisfying $Q = xP$.

- **Elliptic curve computational Diffie-Hellman problem (ECCDHP):** Let $x_1P, x_2P \in E_p(a,b)$, it is almost impossible for $\mathcal{A}_{PPT}$ to figure out $(x_1x_2)P$.

| Notations | Description |
|-----------|-------------|
| $U_i$     | User        |
| $S$       | Server      |
| $Id_i$    | Identity of user $U_i$ |
| $Pw_i$    | Password of user $U_i$ |
| $x$       | Private key of server $S$ |
| $E_p(a,b)$| Elliptic curve over a finite field |
| $P$       | A generator of $E_p(a,b)$ |
| $E_k(\cdot) / D_k(\cdot)$ | The private encryption/decryption with the key $k$ |
| $\|$     | Concatenation operation |
| $\oplus$ | Exclusive-OR operation |
| $H(\cdot)$ | Hash function |
| $SK$      | The session key between $U_i$ and $S$ |
| $\rightarrow$ | Secure channel |
| $\rightarrow$ | Insecure/Open channel |
| $\mathcal{A}$ | Adversary/ malicious attacker |

Table 1. Notations
3. A Brief Review and Supplementary Cryptanalysis of Kumari et al.’s Protocol

3.1 A brief introduction of Kumari et al.’s protocol

This part simply describes Kumari et al.’s protocol [28]. We omit the password changing phase of their protocol. The registration-phase, login and authentication phase are introduced as follows.

3.1.1 Registration phase

User $U_i$ selects identity $ID_i$, password $PW_i$ in dictionary space and picks a random number $b$. First, $U_i$ calculates $RPW_i = h(b \parallel PW_i)$ and sends $\{ID_i, RPW_i\}$ to server $S$ on the secret channel. Second, once the registration-request $\{ID_i, RPW_i\}$ is received, $S$ picks a random number $y_i$ and calculates $N_i = h(ID_i \ || x) \oplus RPW_i$, $Y_i = y_i \oplus h(ID_i \ || x)$, $D_i = h(ID_i \ || y_i \ || RPW_i)$ and $E_i = y_i \oplus h(y \ || x)$. Subsequently, server $S$ sends $N_i$ and a new smart card $SC$ containing $\{Y_i, D_i, E_i, h(.)\}$ to $U_i$. Finally, on receiving $SC$ and $N_i$ from server, $U_i$ computes $A_i = (ID_i \ || PW_i) \oplus b$, $M_i = N_i \oplus b$. Then, $U_i$ inserts $\{A_i, M_i\}$ into $SC$. Thus, $U_i$ obtains a smart card in which $\{A_i, M_i, Y_i, D_i, E_i, h(.)\}$ are stored.

3.1.2 Login and authentication phase

In this part, $U_i(SC)$ and $S$ execute the following steps for login and authentication:

1. $U_i$ inserts his smart card $SC$ into the card reader and inputs correct $ID_i, PW_i$. Then, $SC$ computes $b = (ID_i \ || PW_i) \oplus A_i$, $RPW_i = h(b \parallel PW_i)$ and calculates $h(ID_i \ || x) = M_i \oplus RPW_i \oplus b$, $y_i = h(ID_i \ || x) \oplus Y_i$ and $D_i^* = h(ID_i \ || y_i \ || RPW_i)$. Afterward, $SC$ checks $D_i^* = D_i$. After finishing this verification, $SC$ figures out $h(y \ || x) = y_i \oplus E_i$ and $N_i = M_i \oplus b$. Subsequently, $SC$ selects current timestamp $T_i$ and calculates $CID_i = ID_i \oplus h(N_i \ || y_i \ || T_i)$, $N_i^* = N_i \oplus h(y_i \ || T_i)$, $B_i = N_i^* \oplus RPW_i$, $C_i = h(N_i \ || y_i \ || B_i \ || T_i)$ and $F_i = y_i \oplus (h(y \ || x) \ || T_i)$. Finally, $SC$ sends the login request message $\{CID_i, N_i^*, C_i, F_i, T_i\}$ to $S$ over a public channel.

2. On receiving $\{CID_i, N_i^*, C_i, F_i, T_i\}$ from $SC$, $S$ verifies the timestamp $T_i$ according to the current timestamp. Then $S$ computes $y_i = (h(y \ || x) \ || T_i) \oplus F_i$, $N_i = N_i^* \oplus h(y_i \ || T_i)$, $ID_i = CID_i \oplus h(N_i \ || y_i \ || T_i)$, $B_i^* = h(ID_i \ || x)$ and $C_i^* = h(N_i \ || y_i \ || B_i^* \ || T_i)$. Afterward, $S$ checks $C_i^* = C_i$. If the equation doesn’t, $S$ ends this request, otherwise, $S$ selects the current timestamp $T_{ss}$ and calculates $a = h(B_i^* \ || y_i \ || T_{ss})$. Afterwards, $S$ sends $\{a, T_{ss}\}$ to $SC$.

3. On receiving $\{a, T_{ss}\}$ from $S$, $SC$ verifies the timestamp $T_{ss}$ according to the current timestamp. Then, $SC$ figures out $a^* = h(B_i \ || y_i \ || T_{ss})$ and checks $a_i^* = a_i$.

4. If the aforementioned steps are performed successfully, then $U_i$ and $S$ can figure out the common session key $SK_i = h(B_i \ || y_i \ || T_i \ || T_{ss} \ || h(y \ || x))$.

3.2 Vulnerability analysis of Kumari et al.’s protocol

In this subsection, we prove that the protocol of Kumari et al. [28] can neither resist key-compromise-impersonation attack nor provide perfect-forward-secrecy, except the vulnerability pointed out by Nikooghadam et al. [30].
3.2.1 Perfect-forward-secrecy
According to the analysis of Nikooghadam et al. [30], if a legitimate user $U_j$ acts as an attacker and knows the long-term private key $x$ of $S$, the malicious client $U_j$ obtains the session key between $U_j$ and $S$ by performing the following steps.
1. $U_j$ computes $b_j = (ID_j \parallel PW_j) \oplus A_j$. $RPW_j = h(b_j \parallel PW_j)$. $h(ID_j \parallel x) = M_j \oplus RPW_j$. $y_j = Y_j \oplus h(ID_j \parallel x)$ and $h(y \parallel x) = y_j \oplus E_j$.
2. $U_j$ extracts the values $\{Y_j, M_i, A_i, D_i, E_i\}$ of the $U_i$’s smart card and intercepts the login request message $\{CID_i, N_i', C_i, F_i, T_i\}$ and the respond message $\{a, T_{ss}\}$ to $U_i$ from $S$.
3. $U_j$ calculates $y_i = F_i \oplus (h(y \parallel x) \parallel T_i)$. $N_i = N_i' \oplus (y_i \parallel T_i)$. $ID_i = CID_i \oplus h(N_i \parallel y_i \parallel T_i)$ and $B_i = h(ID_i \parallel x)$.
4. Finally, $U_j$ successfully computes the session key $SK_i = h(B_i \mid y_i \mid T_i') \mid T_{ss} \mid h(y \mid x))$.

3.2.2 Key-compromise-impersonation-attack
If a legitimate user $U_j$ acts as an attacker and compromises the long-term secret key $x$ of $S$, then $U_j$ executes the following steps to impersonate $U_i$ to $S$.
1. $U_j$ computes $b = (ID_j \parallel PW_j) \oplus A_j$. $RPW_j = h(b \parallel PW_j)$. $h(ID_j \parallel x) = M_j \oplus RPW_j$. $y_j = Y_j \oplus h(ID_j \parallel x)$ and $h(y \parallel x) = y_j \oplus E_j$.
2. $U_j$ extracts the values $\{Y_j, M_i, A_i, D_i, E_i\}$ of the $U_i$’s smart card and intercepts the login request message $\{CID_i, N_i', C_i, F_i, T_i\}$.
3. $U_j$ computes $y_i = F_i \oplus (h(y \mid x) \mid T_i)$, $N_i = N_i' \oplus (y_i \mid T_i)$, $ID_i = CID_i \oplus h(N_i \mid y_i \mid T_i)$ and $B_i = h(ID_i \mid x)$.
4. $U_j$ selects a new legitimate timestamp $T_i'$. $U_j$ calculates $CID_i' = ID_i \oplus h(N_i \mid y_i \mid T_i')$. $N_i'' = N_i \oplus h(y_i \mid T_i')$, $C_i' = h(N_i \mid y_i \mid B_i' \mid T_i')$ and $F_i' = y_i \oplus (h(y \mid x) \mid T_i')$.
5. $U_j$ transmits the forged login message $\{CID_i', N_i', C_i', F_i', T_i'\}$ to $S$.
6. Once $\{CID_i', N_i', C_i', F_i', T_i'\}$ from $U_j$ is received, $S$ verifies $T_i'$, if it’s within range, $S$ computes $y_i = F_i \oplus (h(y \mid x) \mid T_i')$, $N_i = N_i' \oplus h(y_i \mid T_i')$, $ID_i = CID_i \oplus h(N_i \mid y_i \mid T_i')$, $B_i = h(ID_i \mid x)$, and $C_i = h(N_i \mid y_i \mid B_i' \mid T_i')$. Afterwards, $S$ verifies whether $C_i = C_i'$, if these are equal, $S$ chooses a timestamp $T_{ss}$ and computes $a' = h(B_i' \mid y_i \mid T_{ss})$.
7. $S$ sends the respond message $\{a', T_{ss}\}$ to $U_j$.
8. Finally, $S$ establishes the session key $SK_i = h(B_i \mid y_i \mid T_i') \mid T_{ss} \mid h(y \mid x)$ with the malicious user $U_j$.

4. Introduction and Cryptanalysis of Nikooghadam et al.’s Protocol
4.1 Review of Nikooghadam et al.’s protocol
4.1.1 Registration part
1. $U_i$ selects his identity $ID_i$, password $PW_i$ in dictionary space, and then picks a random number $r$. Afterward, $U_i$ computes $MPW_i = h(ID_i \parallel r \parallel PW_i)$. $U_i$ sends $\{ID_i, MPW_i\}$ to $S$ on the secret channel.
2. Once the registration-request $\{ID_i, MPW_i\}$ is received, $S$ chooses a random element $N$ and calculates $A_i = h(ID_i \parallel x)$, $B_i = A_i \oplus MPW_i$, $MID_i = E_x(ID_i \parallel N)$. Then, $S$
stores $ID_i$ in his database and takes $\{B_i, MID_i, E_k(\cdot), D_k(\cdot), h(\cdot)\}$ into a new smart card $SC$. Subsequently, $S$ sends $SC$ to $U_i$.

(3) Finally, on receiving $SC$ from the server, $U_i$ inserts $\{r\}$ into $SC$. Thus, $U_i$ gets a smart card in which $\{r, B_i, MID_i, E_k(\cdot), D_k(\cdot), h(\cdot)\}$ are stored.

### 4.1.2 Login & authentication part

$U_i(SC)$ and $S$ can finish login and authentication phase using the following steps:

1. $U_i$ inserts his smart card $SC$ into the card reader and inputs $ID_i, PW_i$. Then, $SC$ computes $A_i = B_i \oplus h(ID_i \parallel r \parallel PW_i)$. Subsequently, $SC$ selects a random element $RN_i$ and the current timestamp $T_i$, and computes $M_1 = E_A(ID_i \parallel RN_i \parallel T_i \parallel MID_i)$. Finally, $SC$ transmits the login-request $\{MID_i, M_i, T_i\}$ to $S$ on public-channel.

2. On obtaining $\{CID_i, N_i', C_i, F_i, T_i\}$ from $SC$, $S$ verifies the timestamp $T_i$ according to the current timestamp. Then, $S$ decrypts $MID_i$ to get $(ID_i \parallel N)$ using his secret element $x$ and figures out $A_i' = h(ID_i \parallel x)$, $D_A(M_1) = (ID_i \parallel RN_i \parallel T_i \parallel MID_i)$.

   Afterwards, $S$ selects random numbers $RN_s$ and $N^{New}_s$. Subsequently, $S$ computes $ID_i^{New} = E_x(ID_i \parallel N^{New}_s)$ and $M_2 = E_{A_i'}(MID_i^{New} \parallel RN_s \parallel ID_i \parallel RN_i)$. Finally, $S$ sends $\{M_2\}$ to $SC$.

3. On receiving $\{M_2\}$ from $S$, $SC$ decrypts $M_2$ to be $(MID_i^{New} \parallel RN_s \parallel ID_i \parallel RN_i)$ using $A_i'$ and verifies $ID_i, RN_i$. Afterward, $SC$ figures out $M_3 = h(RN_s \parallel MID_i^{New} \parallel RN_i)$ and the session key $SK = h(RN_i \parallel A_i \parallel RN_s)$. Then, replaces $MID_i$ with $MID_i^{New}$ by itself. At last, $SC$ is able to get the correct password and identity of $U_i$ as follows:

   (1) $\mathcal{A}$ gets the smart card $SC_i$ of some user $U_i$, then $\mathcal{A}$ can obtain the useful datum $\{B_i, MID_i, r, E_{key}(\cdot), D_{key}(\cdot), h(\cdot)\}$ in $SC_i$ and intercepts the request message $\{MID_i, M_i, T_i\}$. Afterwards, $\mathcal{A}$ is able to get the correct password and identity of $U_i$ as follows:

   (1) $\mathcal{A}$ selects $ID_i^*, PW_i^*$ as identity and password of $U_i$ in the identity space $\mathcal{D}_{ID}$ and password space $\mathcal{D}_{PW}$.

   (2) $\mathcal{A}$ figures out $A_i^* = B_i \oplus h(ID_i^* \parallel r \parallel PW_i^*)$.

   (3) $\mathcal{A}$ uses $A_i^*$ to encrypt the value of $M_i$. If the decryption is failed, then $\mathcal{A}$ repeats 1), 2) and 3) till the decryption becomes successful. Otherwise, $\mathcal{A}$ calculates $D_A(M_i) = (ID_i \parallel RN_i \parallel T_i \parallel MID_i^*)$ and checks whether $MID_i^* = MID_i$. If these are equal, it infers that $ID_i^*, PW_i^*$ are the correct identity and password of user $U_i$.

   By observing the above steps, we find that two guessing factors are used in login phase, that is, $A_i$ and $MID_i$. $A_i$ is the decryption key of $M_i$. On successful decryption, $\mathcal{A}$ continues to verify the second guessing factor transmitted through open channel. Moreover, we can compute the computation time complexity of guessing attack as follows: $O(\mathcal{D}_{ID} \ast \mathcal{D}_{PW} \ast (T_h + T_s))$, where $T_h$ is the computational cost for a hash function computation and $T_s$ is the computational cost for symmetric encryption or decryption, $\mathcal{D}_{ID}$ and $\mathcal{D}_{PW}$.
respectively denote the number of $\mathcal{D}_{ID}$ and the number of $\mathcal{D}_{PW}$. Usually, $|\mathcal{D}_{ID}| \leq |\mathcal{D}_{PW}| \leq 10^{9}$ [32,36,37].

Because of the low entropy of identity and password, $\mathcal{A}$ can successfully get the correct identity and password of user $U_i$ within a polynomial time.

4.2.2 Perfect-forward-secrecy

In the protocol of Nikooghadam et al. [30], if $\mathcal{A}$ knows the long term secret key $x$ of $S$, then $\mathcal{A}$ can obtain the session key between $U_i$ and $S$.

(1) $\mathcal{A}$ eavesdrops on the login request message $\{MID_i, M_i, T_i\}$ and the respond message $\{M_3\}$ of $U_i$.

(2) $\mathcal{A}$ decrypts $MID_i$ using the long term private key $x$ of $S$, that is, $D_x(MID_i) = (ID_i||N)$. Then, $\mathcal{A}$ computes $A_i^t = h(ID_i||x)$.

(3) Afterward, $\mathcal{A}$ decrypts $M_i, M_s$ using $A_i^t$, that is, $D_{A_i^t}(M_i) = (ID_i||RN_i||T_i||MID_i) = (MID_i^{New'}||RN_i||ID_i||RN_i)$, respectively. Thus, $\mathcal{A}$ obtains the values of $\{RN_i, h(ID_i||x), RN_s\}$.

(4) Finally, $\mathcal{A}$ successfully calculates the session key $SK = h(RN_i||h(ID_i||x)||RN_s)$.

4.2.3 Key compromise user impersonation attack

If $\mathcal{A}$ compromises the long-term secret key $x$ of $S$, then $\mathcal{A}$ is able to execute the following steps to impersonate $U_i$ to $S$.

(1) $\mathcal{A}$ firstly gets the login-message $\{MID_i, M_i, T_i\}$ of $U_i$. $\mathcal{A}$ computes $D_x(MID_i) = (ID_i||N)$. Afterwards, $\mathcal{A}$ computes $A_i^t = h(ID_i||x)$.

(2) $\mathcal{A}$ choses a new legitimate timestamp $T_i'$. And then, $\mathcal{A}$ selects a random element $RN_i'$ and figures out $M_i' = E_{A_i}(ID_i||RN_i'||T_i'||MID_i)$.

(3) $\mathcal{A}$ transmits $S$ the forged message $\{MID_i, M_i', T_i'\}$.

(4) Upon $\{MID_i, M_i', T_i'\}$ from $\mathcal{A}$ is received, $S$ checks $T_i'$. If it is invalid, $S$ ends the session. Otherwise, $S$ calculates $(ID_i||N) = D_x(MID_i)$, $A_i' = h(ID_i||x)$ and $D_{A_i'}(M_i) = (ID_i||RN_i'||T_i'||MID_i)$. Afterwards, $S$ chooses two random numbers $RN_s'$, $N_i^{New'}$. Subsequently, $S$ computes $MID_i^{New'} = E_{A_i'}(ID_i||N_i^{New'})$ and $M_s' = E_{A_i'}(MID_i^{New'}||RN_s'||ID_i||RN_i')$.

(5) $S$ sends the challenge message $\{M_s'\}$ to $\mathcal{A}$.

(6) After getting the challenge message from $S$, $\mathcal{A}$ calculates $D_{A_i'}(M_s') = (MID_i^{New'}||RN_s'||ID_i||RN_i')$. Then, $\mathcal{A}$ verifies the validity of $ID_i$ and $RN_i'$. If these are invalid, $\mathcal{A}$ ends this attack. Otherwise, $\mathcal{A}$ continues to calculate $M_i'' = h(RN_s' || MID_i^{New'} || RN_i')$.

(7) $\mathcal{A}$ forwards the response message $\{M_i''\}$ to $S$.

(8) On receiving the response message from $\mathcal{A}$, $S$ computes $M_i'' = h(RN_s' || MID_i^{New'} || RN_i')$. Afterwards, $S$ verifies whether $M_i'' = M_i'$. If these are not equal, $S$ terminates this session. Otherwise, $S$ calculates the session key $SK = h(RN_i' || A_i' || RN_s')$ and believes that he has successfully established this session with the legitimate user. Actually, $\mathcal{A}$ is “the legimate user”.

To sum up, the adversary successfully impersonates the legitimate user to $S$. Therefore, Nikooghadam et al.’s protocol fails to withstand such attack.
5. The Improved Protocol

According to the above cryptanalysis on Nikooghadam et al.’s protocol, first, the information \( \{B_i, r\} \) in smart card and the symmetric encryption key \( A_i \) are used in the login request phase of their protocol, so that the attacker can perform off-line guessing. Second, their protocol does not employ public key cryptography, which is the key technology to preserve forward secrecy. Third, their protocol is incapable of resisting key-compromise-impersonation attack, because of lacking some secret number. However, the main aim of this part is to remove the weakness of Nikooghadam et al.’s protocol by using ECC and some tricks. And we present an improved lightweight authentication protocol using ECC. The improved protocol consists of four parts: initialization part, registration part, login and authentication part and password updating part. The registration part is depicted in Fig. 1. The login and authentication part is depicted in Fig. 2.

| Registration part:                      | Server S                       |
|----------------------------------------|--------------------------------|
| Select \( I_d_i, P_w_i \)               | Public key: \( Q = xP \)       |
| Choose a random element \( r \)         | Private key: \( x \)           |
| \( I_d_i, h(I_d_i \parallel r \parallel P_w_i) \) | Compute \( A_i = H(I_d_i \parallel x \parallel T_i) \) |
|                                       | \( B_i = A_i \oplus H(I_d_i \parallel r \parallel P_w_i) \) |
|                                       | Select a random number \( N \) |
|                                       | \( MId_i = H(I_d_i \parallel N) \oplus A_i \) |
|                                       | Store \{\( B_i, MId_i, P, Q, E_k(\cdot) / D_k(\cdot), H(\cdot)\)} in a new smart card \( SC \) |
| Input \( r \) into \( SC \)            |                                |

**Fig. 1.** Registration part of User \( U_i \)

5.1 Initialization part

\( S \) chooses an elliptic curve \( E_p(a, b) \) over \( F_p \) introduced in “Preliminaries”. Then \( S \) picks a random element \( x \in F_p \) and a hash function \( H(\cdot) \). Subsequently, \( S \) calculates \( Q = xP \). Lastly, \( S \) makes public the parameters \( \{E, Q, H(\cdot)\} \) and preserves \( x \) as its long-term secret key.

5.2 Registration part

(1) User \( U_i \) chooses \( Id_i, Pw_i \) and a random element \( r \) and calculates \( h(I_d_i \parallel r \parallel P_w_i) \). Then, \( U_i \) transmits the registration request \( \{Id_i, h(I_d_i \parallel r \parallel P_w_i)\} \) secretly.

(2) \( S \) selects a random number \( T_i \) as the registration time of \( U_i \). Afterwards, computes \( A_i = H(I_d_i \parallel x \parallel T_i) \), \( B_i = A_i \oplus H(I_d_i \parallel r \parallel P_w_i) \). Subsequently, \( S \) picks a random element \( N \) and computes \( MId_i = H(I_d_i \parallel N) \oplus A_i \). Lastly, \( S \) stores \( T_i \) in its database and distributes a new smart card \( SC = \{B_i, MId_i, P, Q, E_k(\cdot) / D_k(\cdot), H(\cdot)\} \) to \( U_i \).

(3) On receiving \( SC \), user \( U_i \) inserts \( r \) into \( SC \). Therefore, \( SC = \{r, B_i, MId_i, P, Q, E_k(\cdot) / D_k(\cdot), H(\cdot)\} \).

5.3 Login & authentication part

(1) \( U_i \) inserts his smart card into card reader. Then \( U_i \) inputs \( Id_i, Pw_i \). Subsequently, \( SC \) figures out \( A_i = B_i \oplus h(I_d_i \parallel r \parallel P_w_i) \) and picks a random element \( a \).
Afterwards, calculates $C_1 = aP, C_2 = aQ$, $M_0 = E_{C_2}(Id_i \parallel H(A_i) \parallel MId_i)$, $M_1 = H(Id_i \parallel C_2 \parallel A_i \parallel MId_i)$, and transmits $\{C_1, M_0, M_1\}$ to $S$ via a public channel.

| User $U_i$ / SC | Server $S$ |
|-----------------|------------|
| $C_1, M_0, M_1$ | Compute $C_1' = xc_1$, $(Id_i^* \parallel H(A_i^*) \parallel MId_i^*) = D_{C_2}(M_0)$, $A_i = H(Id_i^* \parallel x \parallel T_i)$ and verifies $H(A_i^*) =? H(A_i)$. If these are not equal, $S$ terminates the login request. Otherwise, $S$ computes $M_1^* = H(Id_i^* \parallel C_2 \parallel A_i \parallel MId_i^*)$ and checks $M_1^* =? M_1$. If these are not equal, $S$ ends the next operation. Otherwise, $S$ selects random numbers $b, N_{new}$ and computes $MId_i^{new} = H(Id_i \parallel N_{new}^* \oplus A_i^*)$, $C_3 = (MId_i^{new} \parallel b) \oplus H(A_i \parallel C_2)$ and $M_2 = H(Id_i \parallel MId_i^{new} \parallel A_i \parallel C_2 \parallel C_3 \parallel b)$. Then, $S$ sends $\{C_3, M_2\}$ to $U_i$ via a public channel. |
| $C_2$, $M_2$ | Compute $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MId_i^{new})$ $M_3 = H(MId_i^{new} \parallel SK \parallel Id_i \parallel A_i)$ and checks $M_3 =? M_3$. |
| $C_3$, $M_2$ | Compute $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MId_i^{new})$ $M_3 = H(MId_i^{new} \parallel SK \parallel Id_i \parallel A_i)$ and checks $M_3 =? M_3$. |
| $M_3$ | Compute $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MId_i^{new})$ $M_3 = H(MId_i^{new} \parallel SK \parallel Id_i \parallel A_i)$ and checks $M_3 =? M_3$. |
| $M_3$ | Compute $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MId_i^{new})$ $M_3 = H(MId_i^{new} \parallel SK \parallel Id_i \parallel A_i)$ and checks $M_3 =? M_3$. |

(2) On receiving $\{C_1, M_0, M_1\}$, $S$ computes $C_2' = xc_1$ , $(Id_i^* \parallel H(A_i^*) \parallel MId_i^*) = D_{C_2}(M_0)$, $A_i = H(Id_i^* \parallel x \parallel T_i)$ and verifies $H(A_i^*) =? H(A_i)$. If these are not equal, $S$ terminates the login request. Otherwise, $S$ computes $M_1^* = H(Id_i^* \parallel C_2 \parallel A_i \parallel MId_i)$ and checks $M_1^* =? M_1$. If these are not equal, $S$ ends the next operation. Otherwise, $S$ selects random numbers $b, N_{new}$ and computes $MId_i^{new} = H(Id_i \parallel N_{new}^* \oplus A_i^*)$, $C_3 = (MId_i^{new} \parallel b) \oplus H(A_i \parallel C_2)$ and $M_2 = H(Id_i \parallel MId_i^{new} \parallel A_i \parallel C_2 \parallel C_3 \parallel b)$. Then, $S$ sends $\{C_3, M_2\}$ to $U_i$ via a public channel.

(3) After receiving $\{C_3, M_2\}$, $SC$ figures out $(MId_i^{new} \parallel b) = C_3 \oplus H(A_i \parallel C_2)$ , $M_2^* = H(Id_i \parallel MId_i^{new} \parallel A_i \parallel C_2 \parallel C_3 \parallel b)$ and checks $M_2^* =? M_2$. If these are not equal, $SC$ terminates this session. Otherwise, $SC$ computes $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MId_i^{new})$, $M_3 = H(MId_i^{new} \parallel SK \parallel Id_i \parallel A_i)$ and replaces $MId_i$ with $MId_i^{new}$.

Fig. 2. Login and authentication part
Finally, $SC$ transmits $M_3$ to $S$ via a public channel.

(4) Upon obtaining $M_3$, $S$ calculates the session key $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel M_{Idi_{new}})$, then computes $M'_3 = H(M_{Idi_{new}} \parallel SK \parallel Id_i \parallel A_i)$ and checks $M'_3 = M_3$.

If these are not equal, $S$ ends this session. Otherwise, $S$ accepts this session and the session key $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel M_{Idi_{new}})$.

5.4 Password updating part

After $U_i$ and $S$ have completed the authentication and the session key $SK$ is established, $U_i$ can renew his/her password at will. Firstly, $U_i$ inputs his identity $Id_i$, old password $P_{wi}$ and new password $P_{wi_{new}}$. Then, $SC$ computes 

$$B_{i_{new}} = B_i \oplus H(Id_i \parallel r \parallel P_{wi}) \oplus H(Id_i \parallel r \parallel P_{wi_{new}}).$$

Finally, $SC$ replaces $B_i$ with $B_{i_{new}}$.

**Remark:** To eliminate the shortcomings of Kumari et al.’s and Nikooghadam et al.’s protocols and provide better security, in our protocol, 1. we adopt a pattern that the smart card does not check the correctness of the login, but the correctness of the login is verified by the server; 2. according to [53], in order to obtain perfect forward secrecy, the improved protocol uses elliptic curve cryptography (ECC); 3. in order to resist key-compromise user impersonation attack, the server store a secret element $T_i$ in its database which cannot be leak to the adversary.

6. Heuristic security analysis

6.1 Preserve user anonymity & un-traceability

We suppose that the adversary $A$ has stolen $U_i$’s smart card and has obtained all datum \{$B_i, M_{Idi}, P, Q, E_k(\cdot) / D_k(\cdot), H(\cdot)$\}. In the login process of $U_i$, $A$ eavesdrops all transmitted message \{$C_1, M_0, M_1, C_3, M_2, M_3$\}. Since, these parameters are either protected by hash function or is computed by elliptic curve discrete logarithm cryptography, $A$ is unable to derive the identity $Id_i$ from them in polynomial time. Moreover, those transmitted message are variable in every time communication. Therefore, the presented protocol can provide user anonymity & un-traceability.

6.2 Resist privileged insider attack

During the registration phase, the user $U_i$ sends \{$Id_i, h(Id_i \parallel r \parallel P_{wi})$\} to $S$. The password $P_{wi}$ of $U_i$ is protected by hash function and the secret element $r$, so the inside adversary cannot get the plaintext password of $U_i$. Accordingly, the proposed scheme is immune to such attack.

6.3 Resist replay attack

In our proposed scheme, all transmitted message \{\$C_1, M_0, M_1, C_3, M_2, M_3\} in open channel are different for every communication. Once the adversary replays these message, the server or user can detect the problem. Therefore, it is impossible to perform the replay attack for the adversary in the improved protocol.
6.4 Resist stolen verifier attack

In our improved protocol, suppose that $\mathcal{A}$ steals the verifier table stored in $S$, however, $\mathcal{A}$ still cannot perform any attack. Thereupon, the improved protocol can resist against stolen-verifier-attack.

6.5 Resist off-line password guessing attack

Suppose that $\mathcal{A}$ gets all elements stored in $SC_i$ of $U_i$. On one hand, $\mathcal{A}$ is not able to guess the correct password $Pw_i$ of $U_i$, since, there does not exist any verifying value in these parameters. On the other hand, if $\mathcal{A}$ not only gets these parameters in smart card, but also intercepts the login request message $\{C_1, M_0, M_1\}$, then $\mathcal{A}$ attempts to guess the password $Pw_i$ of $U_i$. In the login request message, $\{M_0, M_1\}$ be used as verifying values. Afterwards, $\mathcal{A}$ can choose identity and password from dictionary space and computes $A_i = B_i \oplus h(Id_i \parallel r \parallel Pw_i)$. However, if $\mathcal{A}$ wants to calculate the corresponding verifying values $\{M_0, M_1\}$, he must know $C_2 = aQ = xC_1$, which is only known to the user and server. Accordingly, $\mathcal{A}$ cannot guess the correct password of $U_i$ by computing the corresponding verifying values. Therefore, our proposed protocol is resistant to off-line dictionary attack.

6.6 Resist key-compromise user impersonation attack

Suppose that if the long-term private element $x$ has been leaked to $\mathcal{A}$, and $\mathcal{A}$ can impersonate the legal user to server, then it infers that the analyzed protocol is vulnerable to key compromise impersonation attack. In proposed protocol, to impersonate the legal user $U_i$, $\mathcal{A}$ must be able to figure out the forged login request message. Since, the random number $T_i$ of $S$ hasn’t been leaked to $\mathcal{A}$, it implies that $\mathcal{A}$ cannot get the correct value of $A_i = H(Id_i \parallel x \parallel T_i)$. Thereupon, $\mathcal{A}$ has no way to forge the legal value of $M_1 = H(Id_i \parallel C_2 \parallel A_i \parallel MID_i)$ and $M_3 = H(MID_i^n \parallel SK \parallel Id_i \parallel A_i)$. Thus, the proposed protocol is immune to key compromise user impersonation attack.

6.7 Resist server impersonation attack

If $\mathcal{A}$ wants to masquerade as $S$, then $\mathcal{A}$ must have to calculate a valid responding message $\{C_3, M_2\}$ for $U_i$. In proposed protocol, firstly, $\mathcal{A}$ captures the login request message $\{C_1, M_0, M_1\}$ and extracts the information $\{B_i, MID_i, P, r, Q, E_k(\cdot) / D_k(\cdot), H(\cdot)\}$ in smart card. Then, $\mathcal{A}$ selects two random numbers $b', N_{new}$. To compute the valid message $\{C_3, M_2\}$, $\mathcal{A}$ must know the value of $\{A_i, C_2\}$ that can compute $MID_i^n$. However, $\mathcal{A}$ is unable to create $C_2$ without the long-term private key $x$ of $S$. Thus, $\mathcal{A}$ cannot forge $C_3$ or even $M_2$. According to above discussion, it is inferred that the improved protocol can be protected against the server impersonation attack.

6.8 Provide mutual authentication

During the login & authentication part of the improved protocol, $U_i$ is authenticated by $S$ by using the equations $H(A_i') =? H(A_i)$ and $M_1' =? M_1$. Subsequently, $S$ by using the equation $M_2' =? M_2$. According to the previous analysis, our improved protocol is immune to impersonation attack. Therefore, $S$ and $U_i$ can carry out authentication smoothly. That is to say, the proposed protocol addresses the requirements of mutual authentication.
### 6.9 Provide perfect forward security

Suppose the adversary can intercept any message over public channels and extracts the data in smart card by side-channel attack. In proposed protocol, though $𝒜$ knows password $P_{w_i}$ of $U_i$ and the long-term private key $x$ of $S$, $𝒜$ still cannot calculate the session key $SK = H(Id_i \parallel C_2 \parallel b \parallel A_i \parallel MI_{id_i}^{new})$, because the key is protected by $b$, $N_{new}^{new}$ and $A_i$. Accordingly, the improved protocol can preserve perfect forward secrecy.

### 7. Security simulation of proposed protocol using AVISPA software

AVISPA [38] is a pushbutton software tool for the automated validation of internet security-sensitive protocols and applications, can simulate the formal security verification for the improved protocol. Here, we give the simulation of the improved protocol by using AVISPA tool that estimates whether our protocol is safe under the Dolev-Yao model [31]. Since AVISPA tool accepts High Level Protocol Specification Language (HLPSL), we firstly provide the HLPSL codes, which are provided in Figs. 3-5, for $U_i$, $S$, the session, goal and the environment, respectively. The analysis results of the proposed protocol are displayed in Figs. 6 and 7. From the simulation results of OFMC and CL-AtSe, it is inferred that the proposed protocol is SAFE against active and passive attacks including replay and man-in-the-middle attacks under Dolev-Yao model.

### 8. BNA-Logic Proof of Proposed Protocol

Here, we give the security proof of the improved protocol using BAN-Logic [39]. We prove that $U_i$ can establish a session initial key with $S$ in the proposed protocol. First, some BAN-Logic notations are listed in Table 2. Second, some BAN-logic postulates are listed in Table 3, and the idealized form, security goals and initiative premises of the improved protocol are formally provided.

1. The idealized form of the proposed protocol is given as follows:
   - **Message-1:** $U_i \rightarrow S$: $C_1$, $(Id_i, C_2, MI_{id_i})_{U_i S}^{A_i}{SK}$, $(Id_i, MI_{id_i}^{new}, U_i \leftarrow S)_{U_i S}^{A_i}{SK}$
   - **Message-2:** $S \rightarrow U_i$: $<MI_{id_i}^{new}, b >_{S}^{M(A_i)_{C_2}}$, $(Id_i, MI_{id_i}^{new}, C_2, C_3, b)_{U_i S}^{A_i}{SK}$

2. Security goals of the proposed protocol are presented as follows:
   - **Goal-1:** $U_i \not\equiv S \equiv U_i {SK} \leftarrow S$
   - **Goal-2:** $U_i \not\equiv S \equiv U_i {SK} \leftarrow S$
   - **Goal-3:** $S \equiv U_i \not\equiv U_i {SK} \leftarrow S$
   - **Goal-4:** $S \not\equiv U_i {SK} \leftarrow S$

3. Initiative premises of the improved protocol are presented as follows:
   - **I-1:** $U_i \equiv \#a$
   - **I-2:** $S \equiv \#b$
   - **I-3:** $U_i \equiv \#MI_{id_i}^{new}$
   - **I-4:** $S \equiv \#MI_{id_i}^{new}$
   - **I-5:** $U_i \equiv U_i {A_i} \leftarrow S$
   - **I-6:** $S \equiv U_i {A_i} \leftarrow S$
   - **I-7:** $S \equiv U_i \not\equiv S \Rightarrow U_i {SK} \leftarrow S$
I-8: $S \equiv U_i \Rightarrow U_i \leftarrow S$

We conduct the BAN-Logic proof of the improved protocol as follows:

- **P-1:** According to Message-2, we have
  \[ U_i \leftarrow (Id_i, MId_i^{new}, C_2, C_3, b) \]

- **P-2:** From P-1, I-5, and Message-meaning rule, we deduce
  \[ U_i \equiv S |~(Id_i, MId_i^{new}, C_2, C_3, b) \]

- **P-3:** By P-2, I-1, I-2, I-3, and Freshness-conjunctenation rule, we infer
  \[ U_i \equiv \#(Id_i, MId_i^{new}, C_2, C_3, b) \]

- **P-4:** By P-3, P-2, and Nonce-verification rule, we deduce
  \[ U_i \equiv S \equiv (Id_i, MId_i^{new}, C_2, C_3, b) \]

- **P-5:** From P-4 and Believe rule, we obtain
  \[ U_i \equiv S \equiv U_i \leftarrow S \]

---

Goal-1

---

### role alice(Ui,S:agent, SKas:symmetric_key, H, Mul: hash_func, Snd, Rcv: channel(dy))
played_by Ui
def=
local State: nat, IDi,PWi,R,X,Ti,VPWi,A,B,P,Q,N,C2,N0,MIdi0,SK:text, Ai,Bi,MIdi,C1,C3,M0,M1,M2,M3:message, Inc: hash_func
const alice_server_a,server_alice_b,subs1,subs2,subs3, subs4,subs5:protocol_id
init State:=0
transition

%/%%Registration phase
1.State=0/\Rcv(start)=|>
State'=1/\R'=new()
/\VPWi'=H(IDi.R'.PWi)
/\secret({PWi},subs1,Ui)
%/%%Send the registration message to server
/\Sndt(IDi,VPWi')_SKas
%/%%Receive the responding registration message from server
2.State=1/\Rcv({Bi'.MIdi'.P.Q}_SKas)=|>
%/%%Login and Authentication Phase
State'=3/\A'=new()
/\Ai'=xor(Bi,VPWi)
/\C1'=Mul(A'.P)
/\C2'=Mul(A'.Q)
/\M0'=xor(H(IDi.H(Ai').MIdi),C2')
/\M1'=H(IDi.C2'.Ai'.MIdi')
%/%%Send the login request message to Server
/\Sndt(C1'.M0'.M1')
/\witness(Ui,S,alice_server_a,C2')
/\request(Ui,S,alice_server_a,C2')
/\secret({C2'},subs2, {Ui,S})
%/%%Receive the respond message from Server
3.State=3/\Rcv(C3'.M2')=|>
State'=5/\B'=new()
P-6: By I-7, P-5, and Jurisdiction rule, we get
\[ U_i \equiv U_i \xleftarrow{SK} S \quad \text{----- Goal-2} \]

P-7: According to Message-1, we have
\[ S \xleftarrow{SK} (Id_i, MId_i, U_i \xleftarrow{SK} S) U_i \xrightarrow{Ai} S \]

role server(S,Ui:agent,
SKas:symmetric_key,
H,Mul:hash_func,
Snd,Rcv:channel(dy))
played_by S
def= local State:nat,
Idi,PWri,Ri,X,N,Ti,VPWi,A,B,P,Q,N0,MIdi0,C2,SK:text,
Ai,Bi,MIdi,C1,C3,M0,M1,M2,M3:message,
Inc:hash_func
const alice_server_a,server_alice_b,subs1,subs2,subs3,
subs4,subs5:protocol_id
init State:=0
transition
%%%Registration phase
%%%Receive the registration message from User
1.State:=0/\Rcv({Idi,VPWi'}_SKas)=|>
State':=2/\X'=new()
/\N'=new()
/\Ti'=new()
/\Ai'=H(Idi,X'.Ti')
/\Bi'=xor(Ai',VPWi')
/\MIdi'=xor(H(Idi,N'),Ai')
/\secret({X',Ti',N'},subs5,S)
%%%Send the respond registration message to User
/\Snd({Bi'.MIdi'.P.Q}_SKas)
%%%Login and Authentication Phase
%%%Receive the login request message from User
2.State:=2/\Rcv({C1'.M0'.M1'}_SKas)=|>
State':=4/\B'=new()
/\N0'=new()
/\C2'=Mul(X,C1')
/\MIdi0'=xor(H(Idi,N0'),Ai)
/\C3'=xor(MIdi0'.B',H(Ai,C2'))
/\M2'=H(Idi,MIdi0'.Ai:C2'.C3'.B')
%%%Send the respond message to User
/\Snd(C3'.M2')
\begin{verbatim}
\%\%\%Receive the respond message from User 3.State:=4/\text{Rcv}(M3')=\Rightarrow
\text{State'}:=6/\text{SK'}:=\text{H(IDi.C2.B.Ai.Midi0)}
///M3':=\text{H(Midi0.SK'.IDi.Ai)}
end role
\end{verbatim}

Fig. 4. Role specification of server \text{S} in HLPSL

- \textbf{P-8:} By P-7, I-5, and Message-meaning rule, we infer
  \[S|\equiv U_i|\sim (Id_i, MId_i^{\text{new}}, U_i \leftrightarrow S).

- \textbf{P-9:} From P-8, I-4, and Freshness-conjunctenation rule, we have
  \[S|\# (Id_i, MId_i^{\text{new}}, U_i \leftrightarrow S).

\begin{verbatim}
role session(Ui, S: agent,
SKas : symmetric_key,
H, Mul: hash_func)
def=
local S1, S2, R1, R2: channel(dy)
composition
alice(Ui, S, SKas, H, Mul, S1, R1)
\%/ server(Ui, S, SKas, H, Mul, S2, R2)
end role
role environment()
def=
const ui,s: agent,
skas : symmetric_key,
h, mul : hash_func,
idi,pwi,r,x,n,vpwi,bi,midi,a,h,p,q,n0,c1,c2,c3,m0,m1,m2,m3:text,
alice_server_a,server_alice_b, subs1,
subs2, subs3, subs4, subs5,subs6: protocol_id
intruder_knowledge = {ui,s, h, mul, bi, midi, a, h, p, q, n0, c1, c2, c3, m0, m1, m2, m3}
composition
session(ui,s, skas, h, mul)
\%/ session(s, ui, skas, h, mul)
end role
goal
secrecy_of subs1
secrecy_of subs2
secrecy_of subs3
secrecy_of subs4
secrecy_of subs5
authentication_on alice_server_a
authentication_on server_alice_b
end goal
environment()
\end{verbatim}

Fig. 5. Roles for session, goal and environment in HLPSL.
• **P-10:** From P-8, P-9, and Nonce-verification rule, we deduce
\[ S \equiv U_i \equiv \left( Id_i, MId_i^{new}, U_i \leftrightarrow S^K \right). \]

• **P-11:** By P-10 and Believe rule, we get
\[ S \equiv U_i \equiv U_i \leftrightarrow S \quad \text{----- Goal-3} \]

• **P-12:** From P-11, I-8, and Jurisdiction rule, we infer
\[ S \equiv U_i \leftrightarrow S \quad \text{----- Goal-4} \]

In summary, since Goals-1-2-3-4 are addressed, \( U_i \) and \( S \) are convinced that the session key is shared successfully between them.

Fig. 6. The experiment result using OFMC.

Fig. 7. The experiment result using CL-AtSe.
Table 2. BAN-Logic notations

| Notations  | Description                        |
|------------|------------------------------------|
| $X \& Y$   | Statements                         |
| $A \& B$   | Principals                         |
| $K$        | Cryptographic encryption key       |
| $A \equiv X$ | $A$ believes on $X$              |
| $A \leftarrow X$ | $A$ sees or receives $X$     |
| $A \mid \neg X$ | $A$ once said $X$                |
| $A \Rightarrow X$ | $A$ controls $X$                |
| $(X)_{K}$  | $X$ is fresh                       |
| $A \leftrightarrow B$ | $A$ and $B$ communicate using shared key $K$ |
| $(X,Y)_{K}$ | Take hash of $X$ and $Y$ using $K$ as key |
| $< X >_{K}$ | $X$ is xor-ed with the key $K$     |

Table 3. BAN-Logic rules

| Rule                        | Description                                             |
|-----------------------------|---------------------------------------------------------|
| Nonce-verification rule     | $A \equiv \#(X), A \mid \equiv B \mid \neg X$           |
| Message meaning rule        | $A \equiv A \leftrightarrow K, A \leftarrow (X)_{K}$    |
| Freshness-conjunctenation   | $A \equiv \#(X)$                                      |
| Believe rule                | $A \equiv B \equiv (X,Y)$                             |
| Jurisdiction rule           | $A \equiv B \Rightarrow X, A \mid \equiv B \mid \equiv X$ |

9. Performance Analysis of improved Protocol with Related Literatures

In this part, we compare the performance of the improved protocol with some related protocols [26-30, 40-44, 54] in terms of computational cost and security performance. Usually, we neglect the lightweight operations such as exclusive-OR and string concatenation. However, the following cryptographic operations are considered: $Th$: the time for executing a hash operation, $Ts$: the time for performing symmetric key encryption/decryption, $Tmm$: an 160-bit modular multiplication, $Tme$: the computational time for an elliptic curve point multiplication, $Tae$: the computational cost for an elliptic curve point addition computation, $Te$: the computational time for an 1024-bit modular exponentiation. According to the experimental results of [45,46], $Th$, $Ts$, $Tmm$, $Tme$, $Tae$ and $Te$ approximately take 0.0023ms, 0.0046ms, 0.001855ms, 2.226ms, 0.0288ms, 3.85ms, respectively.
Table 4. The computational cost in login-authentication phase

| Protocols          | User   | Server | Total               |
|--------------------|--------|--------|---------------------|
| Chang et al. [26]  | 5Th    | 5Th    | 10Th ≈ 0.023ms      |
| Kumari et al. [28] | 8Th    | 7Th    | 15Th ≈ 0.0345ms     |
| Chaudhry et al. [29]| 8Th    | 67h + 2Ts | 147h + 2Ts ≈ 0.0414ms |
| Nikooghadam et al. [30]| 3Th + 2Ts | 3Th + 4Ts | 6Th + 6Ts ≈ 0.0414ms     |
| Chou et al. [40]   | 10Th   | 11Th   | 217h ≈ 0.0483ms     |
| Wen et al. [41]    | 9Th    | 8Th    | 17Th ≈ 0.0391ms     |
| Wang et al. [27]   | 3Te + 8Th | 3Te + 6Th | 6Te + 14Th ≈ 23.1322ms |
| Chen et al. [42]   | 2Te + 2Tmm + 3Th | 2TE + Tmm + 4Th | 4Te + 3Tmm + 7Th ≈ 15.4217ms |
| Mishra et al. [43] | 2Te + 6Th | 2Te + 5Th | 4Te + 117h ≈ 15.4253ms |
| Qu et al. [44]     | 16Tm + 2Tme | 127h + 2Tme | 287h + 4Tme ≈ 8.9684ms |
| Chaudhry et al. [54]| 8Th + 3Tme + 7ae | 6Th + 3Tme | 147h + 6Tme + Tae ≈ 13.417ms |
| **Ours**           | 7Th + 2Tme + Ts | 8Th + Tme + Ts | 15Th + 3Tme + 2T ≈ 6.7217ms |

From Table 4, since the protocols of Chang et al. [26], Kumari et al. [28], Chaudhry et al. [29], Nikooghadam et al. [30], Chou et al. [40], Wen et al. [41] only use hash function and symmetric key cryptographic operations, the computational cost is quite small not exceeding 0.05ms. In order to make the authentication protocol more secure, Wang et al. [27], Chen et al. [42], Mishra et al. [43], Qu et al. [44] and Chaudhry et al. [54] use public key cryptography, such as: ECC, RSA and discrete logarithms on a general group. The computational cost of login-authentication phase in the protocols of Wang et al. [27], Chen et al. [42], Mishra et al. [43], Qu et al. [44] and Chaudhry et al. [54] are approximately 23.1322ms, 15.4217ms, 15.4253ms, 8.9684ms and 13.417ms respectively. While the computational cost of the proposed protocol is approximately only 6.7217ms. Therefore, it illustrates that the improved protocol is more efficient than [27,42-44] under the advantage of public key cryptography.

From Table 5, we observe that Chang et al. [26], Kumari et al. [28], Chaudhry et al. [29], Nikooghadam et al. [30], Chou et al. [40], Wen et al. [41]’s protocols are unable to provide perfect forward secrecy because of only using hash function and symmetric key cryptographic operations in their protocols. Among comparative literature, only our, Chaudhry et al. [29] and Mishra et al. [43]’s protocols can resist key-compromise impersonation attack. To summarize, all these compared literatures are more or less vulnerable to certain security vulnerabilities, except our and Mishra et al.’s protocol. According to Table 4, Mishra et al.’s protocol requires about 15.4253ms in login-authentication phase, while the proposed protocol executes only in 6.7217ms. These illustrate that the improved protocol has better performance than the compared protocols.
Table 5. Comparison of security features

| Protocols              | Features | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 |
|------------------------|----------|----|----|----|----|----|----|----|----|----|
| Chang et al. [26]      |          | No | No | Yes| Yes| No | No | No | Yes| No |
| Kumari et al. [28]     |          | No | Yes| Yes| Yes| No | No | Yes| Yes| No |
| Chaudhry et al. [29]   |          | Yes| Yes| Yes| Yes| No | Yes| Yes| Yes| No |
| Nikooghadam et al. [30]|          | Yes| Yes| Yes| Yes| No | Yes| Yes| Yes| No |
| Chou et al. [40]       |          | No | No | Yes| Yes| No | No | Yes| Yes| No |
| Wen et al. [41]        |          | No | No | Yes| Yes| No | No | Yes| No | No |
| Wang et al. [27]       |          | No | Yes| Yes| Yes| No | Yes| No | Yes| Yes |
| Chen et al. [42]       |          | No | No | Yes| Yes| No | No | Yes| Yes| Yes |
| Mishra et al. [43]     |          | Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes |
| Qu et al. [44]         |          | No | Yes| Yes| Yes| No | No | Yes| Yes| Yes |
| Ours                   |          | Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes |

F1: Preserve user anonymity & un-traceability, F2: Resist privileged-insider attack, F3: Resist replay attack, F4: Resist stolen verifier attack, F5: Resist off-line password guessing attack, F6: Resist (key-compromise) user impersonation attack, F7: Resist server impersonation attack, F8: Provide mutual authentication, F9: Provide perfect forward security.

N/A: means the evaluation indicator is not considered.

10. Conclusion

In this paper, we proved that Kumari et al.’s protocol [28] is vulnerable to key-compromise impersonation attack and cannot provide perfect forward secrecy, while Nikooghadam et al.’s protocol [30] is vulnerable to key compromise impersonation attack, off-line password-guessing attack, and unable to provide perfect forward secrecy. In order to remedy these limitations, we design a new authentication and key agreement protocol based on Nikooghadam et al.’s protocol. By heuristic analysis, AVISPA software simulation and BAN-logic proof, we proved that the improved protocol is more secure than those relevant protocols. By comparison of computational cost, the improved protocol is also more efficient than comparative works under the category of public key cryptography. Therefore, through a comprehensive analysis and evaluation, it is inferred that the proposed protocol is more secure and efficient features. In our future research, we will focus on exploring the more lightweight public key cryptography to design a practical authentication scheme. Moreover, according to [55-58], we will further explore the application of some cryptographic methods applied to image compression and digital watermarking.

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