ROBUST AND PRIVACY PROTECTION AUTHENTICATION
IN CLOUD COMPUTING

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ABSTRACT. In the cloud environments, the cloud user can use low computing devices to connect to the clouds. For checking the identities of the user and the cloud server, they must do mutual user authentication before using the cloud services. Also, the transmitted messages between them must be protected. These environments are different with traditional client-server environments since a cloud user may use many various devices to connect to the cloud server to do authentication. It will face the following problems. The first problem is that some devices only have low computing and memory ability. The second problem is that the cloud user may have many various devices for storing secret sensitive information. If some devices are lost, it is hard to recover the sensitive information stored in these devices. In order to solve all the above problems, we propose a lightweight robust and privacy protection authentication scheme for cloud computing. Our proposed authentication scheme can prevent the insider attack even if the secret information stored in a cloud database is compromised and the offline dictionary attack even if the secret information stored in a user’s device is compromised. Also, the cloud user can freely choose his password to use our proposed authentication scheme.

Keywords: Cloud computing, Information security, Privacy protection, Identity authentication, Low-resource device

1. Introduction. The cloud computing [1,2,8,10,15,22] is growing rapidly in recent years. In a cloud computing environment, the user can transfer some computing loading to the cloud server since the server has high computing ability. Therefore, the user does not need the device that has strong computing ability to connect to the cloud server. In this environment, the user can use many various devices to login to various clouds.

In this environment, the user authentication between the user and the cloud may face the following four problems. The first problem is that the attacker may try to forge the cloud server to get the cloud user’s data and information. The second problem is that the attacker may try to get the cloud user’s identity information from the communication messages between the cloud server and the cloud user. The third problem is that the attacker may try to generate many fake request messages to cause the DDOS attack [11].
The fourth problem is that the secret information stored in the cloud user’s device may be compromised when this device is lost [5,28].

In a cloud environment, the user can use her/his various devices to use the cloud services via authentication [4,13,24,25]. It is very easy to cause the device lost problem since the cloud user may have many portable devices. The cloud devices may store the same secret information. It is very dangerous since some cloud devices may be lost. Therefore, to provide a secure and robust authentication scheme that the user can use her/his various devices to do authentication with the cloud server is very important.

In order to solve all the above problems, we propose a lightweight robust and privacy protection authentication scheme for cloud computing. Our proposed authentication scheme can satisfy the following properties: 1. low communication and computation cost; 2. no password table; 3. free choosing and changing passwords by users; 4. no time-synchronization problem; 5. mutual authentication between the user and the cloud server; 6. revoking the lost card without changing the user’s identity; 7. identity protection; 8. providing session key agreement; 9. preventing the offline dictionary attack with the smart device; 10. no quota limit of the number of a user’s smart devices; 11. without the real user’s identity information in the user’s smart device; 12. increasing the security level of any smart device in the cloud environment.

2. Preliminary.

2.1. Elliptic curve cryptosystem. The elliptic curve cryptosystem (ECC) was introduced by N. Koblitz [18] and V. S. Miller [21] in 1985. The level of security of ECC is based on the elliptic curve discrete logarithm problem (ECDLP). ECC is one of the asymmetric cryptosystems. One characteristic of the ECC is that when the user inputs the same data, the ECC can transform it to different ciphertexts. We introduce DLP in the following. We assume that \( p \) is a large prime number, \( g \) is \( p \)'s primitive root, and \( g \) is less than \( p \). If the attacker can know \([y, g, p]\), it is still difficult to compute \( x \). The key owner can use the formula \( y = g^x \mod p \) to compute the public key \( y \), and send the public key to any person. The sender can use this public key to encrypt the data \( d \). The step is in the following.

1. The sender chooses a random number \( r \).
2. The sender computes \( b = g^r \mod P \) and \( c = d \times y^r \mod P \) and sends \( b \) and \( c \) to the key owner.
3. After the key owner receiving \( b \) and \( c \), the key owner computes \( c \times (bx)^{-1} \mod P \) to obtain the data \( d \).

The elliptic curve cryptosystem (ECC) has two advantages.

1. Low computing cost: ECC is a very strong cryptosystem. Even though the ECC computing cost of 160 bits size is lower than RSA computing cost of 1024 bits, it also has the same security level. Therefore, the ECC can be used in the low computing resources devices like a PDA, a smart card and a cellphone.
2. Randomness: One characteristic of ECC is that when the user inputs the same data, the ECC can transform its different ciphertexts.

2.2. Juang et al.’s scheme.

2.2.1. The parameter generation phase.

1. The server chooses a large prime \( P \) and finds a generator point \( G \).
2. The server selects a random number \( x \) and computes the public key \( PS = (x \times G) \).
3. The server publishes the parameters \((PS, P, EP, G, n)\).
2.2.2. The registration phase.

1. The user selects a password $PW_i$ and a random number $b$, and computes $h(PW_i || b)$. Then the user sends the parameters $ID_i, h(PW_i || b)$ to the server.

2. After the server getting the message, if $ID_i$ is a new identifier, the server sets the card identifier $CI_i = 1$ and stores the record $ID_i, CI_i$ in its registration table. If $ID_i$ is not a new identifier, the server sets the card identifier $CI_i = CI_i + 1$ and stores the record $ID_i, CI_i = CI_i + 1$ in its registration table. Therefore, the server generates $b_i = E_s(h(PW_i || b)||ID_i||CI_i||h(ID_i||CI_i||h(PW_i || b)))$ and $V_i = h(ID_i, s, CI_i)$. The authentication tag is $h(ID_i||CI_i||h(PW_i || b))$. The server issues a smart card to the user. The contained parameters are $b_i, V_i, ID_i, CI_i$.

3. The user stores the parameters $b_i, V_i, ID_i, CI_i, b$ into the smart card.

2.2.3. The precomputation phase.

1. The smart card generates the random number $r$, and computes and stores the parameters $e = (r \times G)$ and $c = (r \times Ps) = (r \times x \times G)$ as a point over $EP$ before the start of the log-in phase.

2.2.4. The log-in phase.

1. The user inserts his smart card into a card reader and inputs his password $PW_i$. Then, the smart card sends the parameters $b_i$ and $E_{V_i}(e)$ to the server.

2. After receiving the message, the server decrypts $b_i$ by the secret key $s$. The server computes $V_i = h(ID_i, s, CI_i)$ and decrypts $E_{V_i}(e)$ to obtain $e$. The server checks if
   (a) the authentication tag is equal to $h(ID_i||CI_i||h(PW_i || b));$
   (b) $ID_i$ is registered;
   (c) $CI_i$ is stored in the table.

   If any of the verifications is false, the server will stop the log-in request. If all of the verifications are true, the server selects a random number $u$ and computes $c = (e \times x) = (r \times x \times G)$ and $Ms = h(c||u||V_i)$. Therefore, the server sends the parameters $u, Ms$ to the smart card.

3. After the smart card getting the message, the smart card computes and checks if $Ms$ is equal to $h(c||u||V_i)$. If it is not, the smart card will stop the log-in phase. Otherwise, the smart card computes $MU = h(h(PW_i || b)||V_i||c||u)$ and $Sk = h(V_i, c, u)$. Then, the smart card sends the parameter $MU$ to the server.

4. After the server getting the message, the server computes and checks that the $MU$ is equal to $h(h(PW_i || b)||V_i||c||u)$. If it is not, the server sends a wrong password message to the user. The user can input the password $PW_i$. Then, the smart card can compute $MU$. Then, the smart card sends the parameter $MU$ to the server again. If the number of the password verifications exceeds the allowed time, the server will stop the log-in request. Otherwise, the server accepts the log-in request and computes $Sk = h(V_i, c, u)$.

2.2.5. The password-changing phase.

1. The user inputs a new password $PW_i^*$ and a new random number $b^*$. Then, the smart card computes $E_{Sk}(ID_i, h(PW_i^* || b^*))$. The smart card sends the parameter $E_{Sk}$ to the server.

2. After the server getting the message, it decrypts $E_{Sk}$ to obtain $ID_i$ and $h(PW_i^* || b^*)$ by $Sk$. The server computes a new $b_i^* = E_s(h(PW_i^* || b^*)||ID_i||CI_i||h(ID_i||CI_i||h(PW_i^* || b^*)))$ and sends the parameter $E_{Sk}(b_i^*)$ to the smart card.

3. After the smart card getting the message, the smart card decrypts it by $Sk$. Then, the smart card stores the new parameters $b_i^*$ and $b^*$ in its memory.
2.3. Sun et al.’s scheme.

2.3.1. The parameter generation phase.
1. The server chooses an elliptic curve $E$ over a finite field $F_p$. The set of all the points on $E$ is denoted by $E(F_p)$.
2. The server chooses a point $G \in E(F_p)$ that the subgroup generated by $G$ has a large order $n$.
3. The server publishes the parameters $p, E, G, n$.

2.3.2. The registration phase.
1. The user selects the sub-identifier $ID_U$. Then, the user sends the sub-identifier $ID_U$ to the server.
2. After the server getting the message, the server checks if this $ID_U$ is valid. If it is true, the server chooses the sub-identifier $ID_S$ and creates the identifier $ID = ID_U \| ID_S$. Then, the server sends an identifier $ID$ to the user. The server generates $V = h(ID\|K_S) \oplus h(PW)$ and $IM = EK_S(ID\|r)$, where the password $PW$ and the identity protection random number $r$ are selected by the server.
3. The server sends the password $PW$ and the smart card parameters to the user, where the smart card parameters are the public parameter $IM$ and the private parameter $V$.

2.3.3. The authentication phase.
1. The user inserts his smart card into a card reader and inputs his password $PW$.
2. The smart card chooses a random integer $rc$ from $[1, n - 1]$ and computes $Gc = rc \times G$. Then, the smart card sends the parameter $IM, Gc$ to the server.
3. After the server receiving the message, the server decrypts the parameter $IM$ by the master secret key $K_S$ to obtain $ID\|r$. The server checks if this $ID$ is valid. If this verification is false, the server stops this phase. If this verification is true, the server creates $Gs = rs \times G$, where the random number $rs$ is selected from the interval $[1, n - 1]$ by the server. The server computes $K_{SU} = h_1(h(ID\|K_S)((rs \times G_c))$ and $M_S = h_2(K_{SU}\|G_c\|Gs)$ and sends the parameters $M_S, Gs$ to the smart card.
4. After the smart card receiving the message, the smart card computes $V' = V \oplus h(PW)$ and $K_{SU} = h_1(V'((rc * G_c))$. Then, the smart card checks if the value $M_S$ is equal to $h_2(K_{SU}\|G_c\|Gs)$. If it is not, the smart card stops this phase. If it is true, the smart card computes $M_U = h_2(K_{SU}\|Gs)$ and sends the parameter $M_U$ to the server.
5. After the server receiving the message, the server checks if the parameter $M_U$ is equal to $h_2(K_{SU}\|Gs)$. If it is not, the server stops this phase. Otherwise, it is successfully authenticated between the server and the user. Then, the server establishes the session key $K_{SU}$.

2.3.4. The password-changing phase.
1. The user inserts his smart card into a card reader and inputs his password $PW$. The user demands to change the password. The user inputs his new password $PW^*$.
2. The user’s smart card computes $V^* = V \oplus h(PW) \oplus h(PW^*)$ and $h(ID\|K_S) \oplus h(PW^*)$. Then, the smart card updates the parameter $V$ with the parameter $V^*$. 
2.4. Singh et al.’s scheme.

2.4.1. The parameter generation phase.
1. The server selects an elliptic curve $E$ over a finite $F_p$. The discrete logarithm problem is hard in $E(F_p)$ and a point $G \in E(F_p)$ that the subgroup is generated by a large order $n$.
2. The server publishes the parameters $p, E, G, n$.

2.4.2. The registration phase.
1. The server creates $V = h(ID||K_S) \oplus h(PW)$ and $IM = EK_S(ID||r)$, where the password $PW$ and the identity protection random number $r$ are selected by the server and the parameter $K_S$ is the private key of the server.

2.4.3. The authentication phase.
1. The user inputs his password $PW$ and the smart card chooses the random integer $rc$ from $[1, n - 1]$. Then, the smart card computes $Gs = rc \times G$ and sends the parameters $IM, Gs$ to the server.
2. After the server receiving the message, the server decrypts the parameter $Gs$ to obtain $ID||r$. The server verifies if this ID is valid. If this verification is false, the server stops this phase. If this verification is true, the server creates $Gs = rs \times G$, $K_{SU} = h(h(ID||K_S)\|(rs \times G_s))$, and $Ms = h(K_{SU}\|Gs\|G_s)$. The server sends the parameters $Ms, Gs$ to the smart card.
3. After the smart card receiving the message, the smart card computes $V' = V \oplus h(PW)$ and $K_{SU} = h(V'\|(rc \times G_s))$. Then, the smart card verifies if the value $Ms$ is equal to $h(K_{SU}\|Gs\|G_s)$. If it is not, the smart card stops this phase. If it is true, the smart card computes $Mu = h(K_{SU}\|Gs)$ and sends the parameter $Mu$ to the server.
4. After the server receiving the message, the server verifies if the parameter $Mu$ is equal to $h(K_{SU}\|Gs)$. If it is not, the server stops this phase. Otherwise, it is successfully authenticated between the server and the user. Then, the server establishes the session key $K_{SU}$ with the user.

2.4.4. The password-changing phase.
1. The user inputs his old password $PW$, and requests the smart card to change the password. Then, the user inputs his new password $PW^*$. The user’s smart card creates $V^* = V \oplus h(PW) \oplus h(PW^*)$ and $h(ID||K_S) \oplus h(PW^*)$. Therefore, the smart card updates the parameter $V$ with the parameter $V^*$.

2.5. Li et al.’s scheme.

2.5.1. The parameter generation phase.
1. The server chooses a large prime $P$ and finds a generator point $G$.
2. The server selects a random number $x$ and computes the public key $PS = (x \times G)$.
3. The server publishes the parameters $(PS, P, EP, G, n)$.

2.5.2. The registration phase.
1. The user selects the password $PW$ and the random string $b$. Therefore, the user sends the parameters $ID, h(pw\|b), N_0$ to the server.
2. After the server receiving the message, the server creates the card identifier \( CI \) and stores the parameters \( ID, CI, N_0 \) in the registration table. The server computes the parameter 
\[
    b_{ID}^{N_0} = E_s(ID || CI || N_0) \oplus h(pw || b) \times h(ID || CI || N_0) \oplus h(pw || b)) \text{ and } V_{ID}.
\]
Then, the server sends the parameters \( b_{ID}^{N_0}, V_{ID}, ID, CI, b \) into the smart card.

3. After the user receiving the message, the user stores the parameters \( b_{ID}^{N_0}, V_{ID}, ID, CI, b \) into the smart card.

2.5.3. The precomputation phase. The smart card generates the random number \( r \). Then, the smart card computes and stores the parameter \( e = (r \times G) \) and \( c = (r \times P_s) \) as a point over \( EP \) before the start of the log-in phase.

2.5.4. The log-in phase.

1. The user inputs his password \( PW \). The smart card sends the parameters \( b_{ID}^{N_0}, E_{V_{ID}}(N_1 || c) \) to the server, in which \( N_1 \in R \{ 0, 1 \}^{64} \).

2. After the server receiving the message, the server decrypts \( b_{ID}^{N_0} \) by the master key \( s \) to obtain \( ID, CI, N_0, h(pw || b) \). Then, the server checks if the parameters \( ID, CI, N_0 \) are in the registration table, and the decryption operation can get the hash tag
\[
    h(ID || CI || N_0) \oplus h(pw || b)).
\]
If this checking is false, the server stops this phase. If this checking is true, the server computes \( V_{ID} = h(ID || s || CI) \) and decrypts \( E_{V_{ID}} \) by \( V_{ID} \) to obtain \( N_1, e \). Then, the server updates the parameters \( ID, CI, N_0 \) in the registration table by \( ID, CI, N_1 \). Then, the server computes \( c = xe \) and \( M_a = h(c || u || V_{ID}) \) and sends the parameters \( Nb_1, u \oplus h_{64}(b_{ID}^{N_1}), M_a \) to the smart card, where
\[
    b_{ID}^{N_1} = E_s((ID || CI || N_1) || (ID || CI) || N_1) \oplus h(pw || b) \times h(ID || CI || N_1) \oplus h(pw || b)).
\]
\( Nb_1 = b_{ID}^{N_1} \oplus (h(N_1 || e || 1)) \oplus h(N_1 || e || 2) \oplus h(N_1 || e || 3) \) and \( h_{64}(b_{ID}^{N_1}) \) is the first 64 bits of \( h(b_{ID}^{N_1}) \).

3. After the smart card receiving the message, the smart card computes the parameter \( b_{ID}^{N_1} \) from \( Nb_1 \). Then, the smart card computes the parameter \( u \) from \( u \oplus h_{64}(b_{ID}^{N_1}) \). The smart card checks if \( M_a \) is equal to \( h(c || u || V_{ID}) \). If this checking is false, the smart card stops this phase. If this checking is true, the smart card believes that the server is real. Then, the smart card updates the parameter \( b_{ID}^{N_1} \) to \( b_{ID}^{N_2} \) and computes the parameter \( M_u = h(pw || b) || V_{ID} || c || u \). The smart card sends the parameter \( M_u \) to the server.

4. After the server receiving the message, the server checks if \( M_u \) is equal to \( h(pw || b) || V_{ID} || c || u \). If this checking is false, the server stops this phase. If this checking is true, the server believes that the smart card is real. Then, the session key is
\[
    k = h(V_{ID} || c || u).
\]

2.5.5. The password-changing phase.

1. When the user wants to change his password, the user must connect to the server.

The user inputs his new password \( pw^* \) and selects a new random parameter \( b^* \). Then, the smart card computes \( E_k((ID || CI || N^*) || h \times (pw^* || b^*)) \) and sends \( E_k \) to the server, where \( N^* \in R \{ 0, 1 \}^{64} \).

2. After the server receiving the message, the server decrypts the parameter \( E_k \) to obtain \( (ID || CI || N^*) || h(pw^* || b^*) \) by the session key \( k \). Then, the server updates the parameters \( ID, CI, N^* \) in the registration table and computes \( b_{ID}^{N^*} \). Then, the server encrypts the parameters \( b_{ID}^{N^*}, ID, CI, N^* \) by the session key \( k \) and sends \( E_k \) to the smart card, where
\[
    b_{ID}^{N^*} = E_s((ID || CI || N^*) || (ID || CI) || N^*) \oplus h(pw^* || b^*) \times h((ID || CI || N^*) || ((ID || CI || N^*) \oplus h(pw^* || b^*)))).
\]
3. After the smart card receiving the message, the smart card decrypts the parameter $E_k$ to obtain $b_{ID}^{N^*}$, $ID$, $CI$, $N^*$ by the session key $k$. Then, the smart card stores the new parameters $b_{ID}^{N^*}$, $V_{ID}$, $ID$, $CI$, $b^*$ in its memory.

3. **Our Proposed Scheme.** In our proposed scheme, it has four participants and five phases. The participants are the cloud user, the cloud user’s device, the cloud server, and the key delegation center (KDC) [17,20]. The phases are the parameter generation phase, the registration phase, the pre-computation phase, the log-in phase, and the password-changing phase. Our proposed authentication mechanism not only uses elliptic curve cryptosystem (ECC) [6,12,14,18,27] to identify the cloud user and the cloud server in the log-in phase, but also uses public one way hash functions [19,23,26] to authenticate the cloud user’s identity information in the registration phase and the log-in phase. Our proposed authentication mechanism uses the related parameters to create the session key in the log-in phase. The cloud user can use the session key [3,7,9,16,24] to encrypt and decrypt the data of communication between the cloud user and the cloud server after the log-in phase. In our proposed authentication mechanism, the cloud user does not scare collusion between the cloud server and the key delegation center (KDC) since the cloud server can get the key stored in the key delegation center (KDC); it cannot decrypt it to get the needed information. Also, the cloud user can choose his password freely.

3.1. **Notations.** The notations for our proposed scheme are defined as follows:
1. $h()$: Public one-way hash function.
2. $E_{AK}()$: Secure symmetric encryption algorithm with the secret key $AK$.
3. $D_{AK}()$: Secure symmetric decryption algorithm with the secret key $AK$.
4. $b$: Random number chosen by the user.
5. $G$: Generator point of a large order.
7. $sk$: Session key agreement’s key.
8. $\|$: String concatenation operator.
9. $x$: Server’s private key based on elliptic curve cryptosystems.
10. $r$: User’s private key based on elliptic curve cryptosystems.
11. $u$: Server’s private key based on elliptic curve cryptosystems.
12. $Ps$: Server’s public key based on elliptic curve cryptosystems.

3.2. **The parameter generation phase.** In this phase the cloud server can generate some parameters as follows:

Step 1. The cloud server can find a generator point $G$ of order $n$, in which $n$ is a large divisor, and $n \times G = O$.

Step 2. The cloud server selects a random number $x$ as its private key and keeps it secretly.

Step 3. The cloud server computes the public key $Ps = (x \times G)$ and publishes the parameters ($Ps$, $G$, $n$).

3.3. **The registration phase.** Any user in this phase will do it only once. The user can use her/his smart device after this phase to verify identity. When the cloud user needs to register a new one in the cloud server, the cloud user should perform the following steps with the cloud server and the KDC (key delegation center).

1. The cloud user $i$ can use any smart device to the cloud server and input its identity information. Then, the smart device creates the AES key $AK$ and encrypts $b$ by $AK$. Then, the smart device computes $h(pu||b)$ and gives $ID_i, h(pu||b), E_{AK}(b)$ to the cloud registration server, where $b$ is a random number chosen by the cloud user.
i. This procedure can be done by the manager of the device in the cloud user $i$'s face.

2. After the cloud server receiving the message, the cloud server creates the changing password identifier $CI_i$, where $CI_i$ is the changing password's counter for the cloud user. If $ID_i$ is not a new user, the cloud server revokes the registration request. If $ID_i$ is a new user, the cloud server will set $CI_i = 1$. If the user will change the password in the future, the cloud server computes $CI_i = CI_i + 1$. The cloud server selects a random number $s$ and generates the parameters $bi = h(ID_i||CI_i||h(pw||b))$ and $VI = h(ID_i||s||CI_i)$. Then, the cloud server stores the parameters $ID_i, CI_i, bi, V_i, E_{AK}(b)$ in the registration table and gives $Message, V_i$ to the smart device, where $Message$ is the successful message by the cloud server. This procedure can be done by the server in the cloud registration's face.

3. After the smart device receiving the message, the smart device encrypts $AK, V_i$ by $pw$ and gives $ID_i, E_{pw}(AK, V_i)$ to the KDC.

4. After the KDC receiving the message, the KDC stores the parameters $ID_i, E_{pw}(AK, V_i)$ in the KDC database and gives $Message$ to the smart device, where $Message$ is a successful notification message.

5. After the smart device receiving the message, the smart device stores the parameters $AK, V_i$. The memory of the smart device contains $AK, V_i$.

3.4. The pre-computation phase. The smart device in this phase can request the cloud server to get the parameters. Then, the smart device has to check if the secret key is in this smart device. The smart device selects a random number and stores some parameters for use in the log-in phase. The smart device should perform the following steps with the cloud server and the KDC (key delegation center).

1. The smart device sends the parameter $ID_i$ to the cloud server.

2. After the cloud server receiving the message, the cloud server can feedback $ID_i$'s $E_{AK}(b)$ and $Message$, where $Message$ is the password changing message by the cloud password changing phase.

3. After the smart device receiving the message, the smart device checks if the smart device has the parameters $AK, V_i$ and $Message$. If it is true, the smart device decrypts $E_{AK}(b)$ by $AK$ to obtain $b$. If the smart device does not have the parameters $AK, V_i$ or $Message$, the smart device has to request the KDC to get the parameter $E_{pw}(AK, V_i)$. Then, the smart device selects a random number $r$ and computes $e = r \times G$ and $c = r \times P_i = r \times x \times G$. Then, the smart device stores the parameters $(c, e, b)$ for use in the log-in phase.

3.5. The log-in phase. When the cloud user wants to login the cloud server, the user must input his password $pw$ and decrypt $E_{AK}(b)$ by $AK$ to obtain $b$. Then, the smart device computes the parameter $h(pw||b)$. In our proposed scheme, the smart device will complete the pre-computation phase before the log-in phase. The cloud user should perform the following steps with the cloud server and the smart device.

1. After the cloud user inputs the password and the smart device has finished the pre-computation phase, the smart device encrypts the parameters $h(pw||b)$ and $e$ by $V_i$ and sends $E_{V_i}(h(pw||b), e)$ to the cloud server, where $V_i = h(ID_i||s||CI_i)$.

2. After the cloud server receiving the message, the cloud server decrypts the parameter $E_{V_i}$ by $V_i$ to obtain $h(pw||b)$ and $e$. The cloud server computes the parameter $bi^*$, where $bi^* = h(ID_i||CI_i||h(pw||b))$. Then, the cloud server checks if $bi^*$ is equal to $bi$. If it is false, the cloud server sends a wrong password message to the user. The user inputs the password $pw$ and $b$ to compute $h(pw||b)$. Then, the smart device
sends the parameter $h(pw||b)$ to the cloud server again. If $b^*$ is equal to $b$, the cloud server selects a random number $u$ and computes $c = e \times x = r \times x \times G$ and $Ms = h(Vi||c||u)$. Then, the cloud server sends the parameters $u$ and $Ms$ to the smart device.

3. After the smart device receiving the message, the smart device computes $Ms$ and checks if the parameter $Ms$ is equal to $h(Vi||c||u)$. If it is not, the smart device revokes the log-in phase. Otherwise, the smart device computes $Mu$ and $sk$, where $Mu = h(h(pw||b)||V_i||c||u)$ and $sk = h(V_i||c||u)$. Then, the smart device sends the parameter $Mu$ to the cloud server. At this time, the cloud server is authenticated by the smart device.

4. After the cloud server receiving the message, the cloud server computes $Mu$ and checks if the parameter $Mu$ is equal to $h(h(pw||b)||V_i||c||u)$. If it is not, the cloud server revokes the log-in phase. Otherwise, the cloud server accepts the log-in request and computes a session key $sk$, where $sk = h(V_i||c||u)$. At this time, the smart device is authenticated by the cloud server. Both sides can use the session key $sk$ to decrypts and encrypts the messages of communication.

3.6. The password-changing phase. The cloud user can change his password in this phase when the user thinks that she/he should do it or the user lost his smart device any time. If the cloud user’s password is changed successful, the smart device can update the new parameter $Vi^*$ in the pre-computation phase. When the cloud user needs to change his password, the cloud user needs to agree on a session key with the server through the log-in phase in advance.

1. After the user inputs his new parameters $pw^*$ or $b^*$ and the smart device has finished the log-in phase. The smart device checks if $b$ has changed. If it is true, $E_{AK}(b) = E_{AK}(b^*)$. If $b$ has not been changed, $E_{AK}(b) = E_{AK}(b)$. Then, the smart device encrypts the parameters $h(pw^*||b^*)$, $E_{AK}(b)$ by $sk$ and sends $E_{sk}(h(pw^*||b^*), E_{AK}(b))$ to the cloud server, where $sk = h(V_i||c||u)$.

2. After the cloud server receiving the message, the cloud server decrypts the parameter $E_{sk}$ by $sk$ to obtain $h(pw^*||b^*)$ and $E_{AK}(b)$. Then, the cloud server selects a random number $s$ and computes $CI_i$, $bi^*$, $Vi^*$, where $CI_i = CI_i + 1$, $bi^* = h(ID_i||CI_i || h(pw^*||b^*))$ and $Vi^* = h(ID_i||s||CI_i)$. Then, the cloud server encrypts the parameter $Vi^*$ by $sk$ and stores the parameters $CI_i$, $bi^*$, $Vi^*$, $E_{AK}(b)$. Then, the cloud server sends the parameters $Message$ and $E_{sk}(Vi^*)$ to the smart device, where $Message$ is the password changing successful message by the cloud server.

3. After the smart device receiving the message, the smart device decrypts $E_{sk}$ by $sk$ to obtain $Vi^*$ to store the parameter $Vi^*$ in the smart device. Then, the smart device encrypts the parameters $AK$, $Vi^*$ by $pw$ and sends $ID_i$ and $E_{pw}(AK, Vi)$ to the KDC.

4. After the KDC receiving the message, the KDC stores the parameters $ID_i$, $E_{pw}(AK, Vi)$ in the KDC database and gives $Message$ to the smart device, where $Message$ is successful message by the KDC.

4. Discussion.


4.1.1. Mutual authentication. In our proposed scheme, the goal of mutual authentication is to create a robust and powerful session key $sk$ between the cloud user and the cloud server. In Step 2 of the log-in phase of our proposed scheme, after the smart device receiving $u$ and $Ms$ from the cloud server, it will compute $Ms$ and verify if $Ms =$
4.1.5. Preventing the insider attack.

In our proposed scheme, we delegate the parameters $ID_i, CI_i, bi, Vi, E_{AK}(b)$ in the cloud registration table. When the cloud user loses his smart device or gets a new cloud device, it can change his password in the password-changing phase and update two keys $AK, Vi$. Therefore, the attacker cannot decrypt the parameter $E_{AK}(b)$ to create the parameter $E_{Vi}(h(pw||b), e)$. Therefore, the attacker cannot pass the checking to use the replay attack to login the log-in server.

4.1.3. Preventing the offline dictionary attack with the lost smart device. The traditional methods would store the data with the high secret information into the device or the smart card. Different with the traditional methods, in our proposed scheme, the smart device does not spend a lot of resources to store parameters, because the parameters $ID_i, E_{pw}(AK, Vi)$ are stored in the key delegation center. Therefore, if the attacker gets the user’s smart device and tries to get the information in the device, it is not useful. The user’s smart device does not contain the parameter $pw$. Even if the attacker gets the smart device, it also is unable to forge the parameter $h(pw||b)$ to login the log-in server.

4.1.4. Using in the cloud environment with any smart device. The traditional methods would store the data with the high secret information into the device or the smart card. In our proposed scheme, we delegate the parameters $ID_i, CI_i, bi, Vi, E_{AK}(b)$ in the cloud registration table. When the cloud user lost his smart device or get a new cloud device, it can change his password in the password-changing phase and update two keys $AK, Vi$ with any smart device in the pre-computation phase. Therefore, the user’s rights and interests will not be affected.

4.1.5. Preventing the insider attack. In this attack, the insider may use his authority to get a user’s password. In our proposed scheme, the smart device computes the parameter $h(pw||b)$ with hash function before sending it to the cloud log-in server. Therefore, the stored password in the server database is encrypted. Our proposed scheme can prevent this attack because the attacker cannot get the complete password parameter $pw$.

4.2. Cost and functionality consideration.

4.2.1. No password table. In the registration phase, the cloud server always needs the password table to store the cloud user’s password. It not only wastes the database storage memory, but also increases the risk of insider attack. In our proposed scheme, the hashed password with a random number $h(pw||b)$ is encrypted in the parameter $bi = h(ID_i||CI_i||h(pw||b))$. It can increase the security level of the log-in phase.
4.2.2. **Choosing and changing passwords by users.** In Li’s scheme, in order to increase the entropy of the password, the server always gives the random password to the user, but this password is hard to remember for user. Therefore, if the user wants to inquire or change her/his password. It will increase the extra cost for the server. In our proposed scheme, the cloud user can choose his password $pw$ and the random number $b$ to do authentication. It would increase the entropy of the password. The random number $b$ will be encrypted by $AK$. Then, the ciphertext will be sent to the key delegation center to store it. It not only can increase the entropy of the password and the high security level, but also can provide the funtion to choose and change the password.

4.2.3. **No time-synchronization problem.** In the log-in phase, in order to prevent the replay attack, timestamps can be used to prevent this problem. This approach will cause the time-synchronization problem. In our proposed scheme, we use two nonces $r$ and $u$ to compute $Ms$ and $Mu$. Challenge and response between the user’s smart device and the cloud login server is used in our scheme for preventing the replay attack. Therefore, we do not have the time-synchronization problem in our proposed scheme.

4.2.4. **No quota limit of the number of a user’s smart devices.** In the registration phase, the user’s smart device encrypts the parameter $b$ by the key $AK$ and stores the ciphertext in the cloud server. In the pre-computation phase, the user’s smart device checks if the smart device does not have $AK, Vi$ or $Message$. If yes, the smart device has to request the key delegation center to get the new parameter $E_{pw}(AK, Vi)$. It can prevent the user from logging the server with the new smart device. In the password-changing phase, the parameter $CI_i$ changes every time when the user changes his password. Therefore, the parameter $Vi$ will be different when the parameter $CI_i$ is changed. Then, the smart device sends the parameters $ID_i$, $E_{pw}(AK, Vi)$ to the key delegation center. After receiving $ID_i$ and $E_{pw}(AK, Vi)$, the key delegation center stores the parameters $ID_i$ and $E_{pw}(AK, Vi)$ in the key delegation center database and sends $Message$ to the smart device.

4.2.5. **Identity protection.** In our proposed scheme, there are two kinds of the identity protection: 1. identity protection of the user’s smart device; 2. identity protection of communication between the cloud server and cloud user. In identity protection of the user’s smart device, the user’s smart device does not store any personal information or the high secret information in the smart device. It only has encryption or decryption operation keys $AK$ and $Vi$. In identity protection of communication between the cloud server and cloud user, it only sends the parameters $h(pw||b)$ and $e$. The parameters are encrypted by $Vi$. Therefore, the attacker cannot get the cloud user’s identity information of communication between the cloud server and the cloud user.

4.2.6. **Providing session key agreement.** After the log-in phase, any communication can use the session key to encrypt or decrypt the messages. In the pre-computation phase of our proposed scheme, the user’s smart device will choose the nonce $r$. Then, the cloud log-in server chooses the nonce $u$ in the log-in phase. The nonces will be different every time. After this phase, the cloud log-in server and the user’s smart device can create the session key parameter $sk$ by himself.

4.2.7. **Without any user’s identity information in the user’s smart device.** We assume that the attacker can get the smart device. She/he will use any tools to get the information in the smart device. In our proposed scheme, we can solve the smart device lost problem because we store the user’s identity information and the encryption parameters in the cloud server and the key delegation center. Therefore, the user’s smart device only temporarily stores the parameters $AK$ and $Vi$ in the cloud device.
4.2.8. Low communication and computation cost. In P1 of Table 1, our scheme, Juang et al.’s scheme [24], Sun et al.’s scheme [4], Singh et al.’s scheme [13], and Li et al.’s scheme [25] use the password. The password length is 128 bits. In P2 of Table 1, our scheme has the parameters \([AK, Vi]\). The memory length is 128 + 128 = 256 bits. Juang et al.’s scheme [24] has the parameters \([bi, Vi, IDi, CIi, b]\). The memory length is 384 + 128 + 32 + 32 + 64 = 640 bits. Sun et al.’s scheme [4] has the parameters \([V, IM]\). The memory length is 128 + 128 = 256 bits. Singh et al.’s scheme [13] has the parameters \([V, IM]\). The memory length is 128 + 128 = 256 bits. Li et al.’s scheme [25] has the parameters \([b; N_0; ID; V_ID; ID; CI]\). The memory length is 384 + 128 + 32 + 32 + 64 = 640 bits. In P3 of Table 1, our scheme has the parameters \([E; V_i(h(pw||b), e), u, Ms, Mu]\). The memory length is 384 + 64 + 128 + 128 = 704 bits. Juang et al.’s scheme [24] has the parameters \([bi; E; V_i(e), u, Ms, Mu]\). The memory length is 384 + 384 + 64 + 128 + 128 = 1088 bits. Sun et al.’s scheme [4] has the parameters \([IM; GC; MS; GS; MU]\). The memory length is 128 + 326 + 128 + 326 + 128 = 1036 bits. Singh et al.’s scheme [13] has the parameters \([IM; GC; MS; GS; MU]\). The memory length is 128 + 326 + 128 + 326 + 128 = 1036 bits. Li et al.’s scheme [25] has the parameters \([b; N_0; ID; V_ID; ID; CI; b; N_1e; N_1e; e; Nb1, u + h64(b^N_1e), MS, MU]\). The memory length is 896+576+128 = 1600 bits. The detail efficiency comparison among our scheme and related schemes is shown in Table 1.

Table 1. The communication and the storage cost comparison among our scheme and related schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our scheme</td>
<td>128</td>
<td>256</td>
<td>704</td>
</tr>
<tr>
<td>Juang et al.’s scheme [24]</td>
<td>128</td>
<td>640</td>
<td>1088</td>
</tr>
<tr>
<td>Sun et al.’s scheme [4]</td>
<td>128</td>
<td>256</td>
<td>1036</td>
</tr>
<tr>
<td>Singh et al.’s scheme [13]</td>
<td>128</td>
<td>256</td>
<td>1036</td>
</tr>
<tr>
<td>Li et al.’s scheme [25]</td>
<td>128</td>
<td>640</td>
<td>1600</td>
</tr>
</tbody>
</table>

P1: Password length  
P2: Memory for storing the cryptographic parameters in a smart device  
P3: Communication cost of the login for cryptographic parameters

In Table 2, we let \(Hash\) be the time of the one hashing operation, \(Sym\) be the time of the one symmetric encryption or decryption operation, \(EC_M\) be the time for the multiplication operation of a number over an elliptic curve, \(M\) be the time for the modular multiplication. We assume that \(EC_M \approx 29 M\) and \(EXP \approx 240 M\), and they are referenced in [12]. We assume that \(hash \approx 0.4 M\) and \(sym \approx 0.4 M\), and they are referenced in [14,27]. We assume that an elliptic curve over a 163-bit field has the same security level as 1024-bit public key cryptosystems such as the RSA or the Diffie-Hellman cryptosystem. In P1 of Table 2, our scheme needs 2 \(Hash\) operations. Juang et al.’s scheme [24] needs 3 \(Hash\) operations. Sun et al.’s scheme [4] needs 2 \(Hash\) operations and 1 \(Sym\) operations. Singh et al.’s scheme [13] needs 2 \(Hash\) operations and 1 \(Sym\) operations. Li et al.’s scheme [25] needs 2 \(Hash\) operations and 3 \(Sym\) operations. In P2 of Table 2, our scheme, Juang et al.’s scheme [24] and Li et al.’s scheme [25] need 2 \(EC_M\) operations. Sun et al.’s scheme [4] and Singh et al.’s scheme [13] do not need the computation cost of the cloud user’s device of the pre-computation phase. In P3 of Table 2, our scheme needs 3 \(Hash\) operations and 1 \(Sym\) operations. Juang et al.’s scheme [24] needs 3 \(Hash\) operations and 3 \(Sym\) operations. In P4 of Table 2, our scheme needs 4 \(Hash\) operations and 2 \(Sym\) operations. Singh et al.’s scheme [13] needs 4 \(Hash\) operations and 2 \(Sym\) operations. Li et al.’s scheme [25] needs 8 \(Hash\) operations and 4 \(Sym\) operations. In P4 of Table 2, our scheme needs 4 \(Hash\) operations and 1 \(Sym\) operations and 1 \(EC_M\) operations. Juang et al.’s scheme
[24] needs 4 Hash operations and 2 Sym operations and 1 EC_M operations. Sun et al.’s scheme [4] needs 4 Hash operations and 1 Sym operations and 2 EC_M operations. Singh et al.’s scheme [13] needs 4 Hash operations and 1 Sym operations and 2 EC_M operations. Li et al.’s scheme [25] needs 10 Hash operations and 10 Sym operations and 1 EC_M operations. The detail efficiency comparison among our scheme and related schemes is shown in Table 2.

Table 2. The computation cost comparison among our scheme and related schemes

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our scheme</td>
<td>2Hash + 1.2M</td>
<td>2EC_M + 5.8M</td>
<td>3Hash + 1Sym + 1.6M</td>
<td>1EC_M + 1Sym + 0.8M + 4Hash + 31M</td>
</tr>
<tr>
<td>Juang et al.’s scheme [24]</td>
<td>3Hash + 1Sym + 1.2M</td>
<td>2EC_M + 5.8M</td>
<td>3Hash + 1Sym + 1.6M</td>
<td>1EC_M + 2Sym + 31.4M</td>
</tr>
<tr>
<td>Sun et al.’s scheme [4]</td>
<td>2Hash + 1Sym + 1.2M</td>
<td>NA</td>
<td>2EC_M + 4Hash</td>
<td>2EC_M + 1Sym + 0.8M + 4Hash + 60M</td>
</tr>
<tr>
<td>Singh et al.’s scheme [13]</td>
<td>2Hash + 1Sym + 1.2M</td>
<td>NA</td>
<td>2EC_M + 4Hash</td>
<td>2EC_M + 1Sym + 0.8M + 4Hash + 60M</td>
</tr>
<tr>
<td>Li et al.’s scheme [25]</td>
<td>2Hash + 3Sym + 2M</td>
<td>2EC_M + 5.8M</td>
<td>8Hash + 4Sym + 4Sym + 4.8M</td>
<td>1EC_M + 10Sym + 37M</td>
</tr>
</tbody>
</table>

P1: The computation cost of the registration for the server
P2: The computation cost of the pre-computation phase for the cloud user’s device
P3: The computation cost of the login for the user’s device
P4: The computation cost of the login for the server

The detail functionalities comparison among our scheme and related schemes is shown in Table 3.

Table 3. The functionality comparison

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
<th>P11</th>
<th>P12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our scheme</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Juang et al.’s scheme [24]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun et al.’s scheme [4]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Singh et al.’s scheme [13]</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Li et al.’s scheme [25]</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

P1: Low communication and computation cost
P2: No password table
P3: Choosing and changing passwords by users
P4: No time-synchronization problem
P5: Mutual authentication
P6: Revoking the lost cards without changing the user’s identity
P7: Identity protection
P8: Providing session key agreement
P9: Preventing the offline dictionary attack with the smart device
P10: No quota limit of a user’s smart device
P11: Without any user’s identity information in the user’s smart device
P12: Preventing the insider attack

5. Conclusions. In the cloud environment, the cloud server has more computing and storage ability. The user can transfer the major computing loading to the cloud and can store the secret information in the cloud. This will cause that an attacker tries to get this valuable information and do various attacks. Therefore, in this environment, how to provide a secure authentication mechanism that the user can use many various devices to...
do authentication and to solve the device lost problem is very important. In this paper, we proposed a lightweight robust and privacy protection authentication scheme for cloud computing. Our proposed scheme can solve the time-synchronization problem, the offline dictionary attack with the smart device, the replay attack, the offline dictionary attack with the lost smart device, and the insider attack. In addition, our proposed scheme can provide many advantages. The advantages are mutual authentication, using in the cloud environment with any smart device, low communication and computation cost, no password table, no quota limit of the number of a user’s smart devices, identity protection, providing session key agreement and without any user’s real identity information in the user’s smart device.

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