An Efficient and Robust Anonymous Authentication Scheme in Global Mobility Networks

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Abstract

Anonymous user authentication is an essential security mechanism for roaming services in global mobility networks (GLOMONET). Recently, Zhao et al. propose a two-factor anonymous authentication scheme to achieve mutual authentication and session key establishment between the mobile user (MU) and a foreign agent (FA). This paper shows that their scheme has some security vulnerabilities and operational inefficiencies: (1) The scheme fails to protect against a strong replay attack, (2) it is impractical because it requires the predistribution of system parameters, and (3) it is inefficient because of unnecessary encryption/decryption operations. To remedy these weaknesses, this paper proposes a novel anonymous authentication scheme using a smart card. The proposed scheme provides security requirements such as user anonymity, perfect forward secrecy, correct password change, authentication when the MU is located in the home network (HN), and no predistribution of system parameters. In addition, the proposed scheme is secure against various attacks such as impersonation attack, replay attack, off-line password attack, insider attack, stolen-verifier attack, and local password attack. A performance analysis and a comparison with existing schemes show that the proposed scheme is more suitable for low-power and resource-limited mobile environments.

Keywords: Mutual authentication, User anonymity, Session key agreement, Smart card

1. Introduction

In a global mobility network (GLOMONET), a mobile user (MU) can access global services through its relationship with the nearest network access point [1]. If the MU wants to roam into a foreign network, mutual authentication between the MU and a foreign agent (FA) is required with the help of the MU's home agent (HA). Many anonymous authentication schemes have been proposed to preserve personal privacy during roaming access to the FA. Such schemes are based mainly on the two-factor authentication technology to enhance the level of security. Here the two-factor usually refers to the password and smart card of the MU [2, 3].

The main security functions of the anonymous authentication scheme are mutual user authentication and session key establishment between the MU and the FA. As pointed out in [4], a strong user authentication scheme should satisfy the following requirements: (1) user anonymity, (2) low communication costs and computational complexity, (3) single registration, (4) update session key periodically, (5) user friendly, (6) no password/verifier table, (7) update password securely and freely, (8) prevention of fraud, (9) prevention of replay attack, (10) security, and (11) the provision of an authentication scheme when the user is located in the home network (HN).

In 2004, Zhu and Ma [5] propose the first anonymous authentication scheme for wireless communications. However, Lee et al. [2] show that their scheme cannot achieve mutual authentication and perfect backward secrecy and that the scheme is vulnerable to the forgery attack and propose an enhanced scheme with minor modifications. Later, Wu et al. [3] and Chang et al. [6] independently find that Lee et al.'s scheme does not provide user anonymity under the forgery attack. Unfortunately, Youn et al. [7] show that both Wu et al. and Chang et

al.'s schemes do not provide anonymity. In 2011, He et al. [4] demonstrate that Wu et al.'s scheme is vulnerable to several attacks and propose an improved scheme. However, Li and Lee [8] further show that He et al.'s scheme does not satisfy security properties such as user friendliness, fairness in key agreement, and user anonymity. In 2012, Mun et al. [9] analyze Wu et al.'s scheme, pointing out that their scheme also cannot achieve user anonymity, perfect forward secrecy, and the protection of the legal user's password, and then propose an enhanced authentication scheme. Nevertheless, Zhao et al. find that Mun et al.'s scheme is also vulnerable to both impersonation attack and insider attack.

Recently, some new anonymous authentication schemes have been proposed [10–17]. This paper investigates these schemes based on security requirements for secure roaming services in GLOMONET and shows that most have several weaknesses. Unfortunately, the results show that Zhao et al.'s scheme [10] is vulnerable to a strong replay attack and is impractical in terms of the pre-distribution of system parameters. In addition, because their scheme includes useless encryption/decryption operations for open messages, it is inefficient in terms of computational complexity. To overcome these weaknesses and inefficiencies, this paper proposes an effective and secure anonymous authentication scheme designed to satisfy various security requirements and be suitable for low-power and resource-limited mobile devices by reducing computational costs.

The rest of this paper is organized as follows: Section 2 provides some mathematical preliminaries that are useful for a security analysis. Section 3 reviews Zhao et al.'s scheme. Section 4 shows this scheme's security weaknesses and points out its inefficiencies. Section 5 proposes a novel anonymous authentication scheme, and Sections 6 and 7 provide a security analysis of the proposed scheme and a performance comparison with existing schemes, respectively. Section 8 concludes.

2. Mathematical Preliminaries

This section discusses the one-way hash function and two computational problems: the discrete logarithm problem (DLP) and the computational Diffie-Hellman problem (CDHP), which are useful for analyzing the security of anonymous authentication schemes described in this paper.

2.1. One-way Hash Function

The one-way hash function $h : \{0, 1\}^* \rightarrow \{0, 1\}^l$ takes a message of any length as the input and produces a fixed-length output called as a hash value or message digest. A hash function has the following cryptographic properties [18]:

- (1) Pre-image resistance: Given a hash value y , it should be difficult to find any input message x such that $y = h(x)$. This property is related to that of the one-way function. A hash function that lacks this property is vulnerable to the pre-image attack.
- (2) Second pre-image resistance: Given an input x_1 , it should be difficult to find another input x_2 such that $x_1 \neq x_2$ and $h(x_1) = h(x_2)$. A hash function that lacks this property is vulnerable to a second pre-image attack.
- (3) Collision resistance: It should be difficult to find two different input messages x_1 and x_2 such that $x_1 \neq x_2$ and $h(x_1) = h(x_2)$. Such an input pair is called a hash collision.

One of the most important cryptographic applications using the one-way hash function is the integrity verification of messages. In addition, the hash function can be applied to generate the message authentication code (MAC) or sign on the message to provide message authentication and non-repudiation services.

2.2. Discrete Logarithm Problem

Given elements g and y of the multiplicative group Z_p^* , the discrete logarithm problem (DLP) is the problem of finding a number x such that $g^x = y \bmod p$. If p is assumed to be a large integer, then it is

difficult to determine x given g , p , and y . The difficulty of the discrete logarithm problem is the basis for the security of several cryptographic systems such as the Diffie-Hellman key agreement [19], the digital signature algorithm, and their elliptic curve cryptography analogs [20].

2.3. Computational Diffie-Hellman Problem

Given an element g and values of $X = g^x \bmod p$ and $Y = g^y \bmod p$, the computational Diffie-Hellman problem (CDHP) is the problem of finding the value $g^{xy} \bmod p$. It is difficult to find $g^{xy} \bmod p$ for given g , p , X , and Y if p is a large integer. For example, in the Diffie-Hellman key agreement protocol, even if an attacker eavesdrops $X = g^x \bmod p$ and $Y = g^y \bmod p$ during the exchange process, the attacker cannot compute the common key $g^{xy} \bmod p$ shared between two parties.

3. Review of Zhao *et al.*'s Scheme

This section reviews Zhao *et al.*'s anonymous authentication scheme [10]. This scheme consists of four phases: registration phase, authentication and session key establishment phase, update session key phase, and update password phase. This scheme contains the authentication and session key establishment phase when the MU is located in the HN. This paper briefly describes the registration and authentication and session key establishment phases of Zhao *et al.*'s scheme. Notations and computational operations for a simple description of schemes in this paper are listed in Table 1.

3.1. Registration Phase

If the MU wants to be a legal client, then it must first register to its HA through the following steps (Figure 1 details the registration phase):

Step R1: The MU chooses the identity ID_{MU} and password PW_{MU} and generates a random number N_{MU} . The MU then sends ID_{MU} and $h(PW_{MU} || N_{MU})$ to the HA through a secure channel.

Step R2: After receiving the registration message from the MU, the HA computes $Q = h(ID_{MU} || y) \oplus h(PW_{MU} || N_{MU})$ and $H = h(ID_{MU} || h(PW_{MU} || N_{MU}))$, where y is the HA's secret master key. Then the HA stores the information $\{Q, H, C, ID_{HA}\}$ in a smart card and issues the smart card to the MU through a secure channel.

Step R3: Upon receiving the smart card, the MU inputs the previously generated random number N_{MU} into the smart card

3.2. Authentication and Session Key Establishment Phase

If the MU roams into foreign network, it must prove itself to the FA as a legal user and verify the identity of the FA. The authentication and session key establishment phase of Zhao *et al.*'s scheme is described through the following steps (Figure 2 details this phase):

Table 1. Notations and Computational Operations

Notation	Description
MU, FA, HA	Mobile user, foreign agent, home agent
ID_X	Identity of an entity X
PW_X	Password of an entity X
$Cert_X$	Certificate of an entity X
S_X	Private key of an entity X
P_X	Public key of an entity X
SK	Session key shared between the MU and the FA
P	A point of the additive elliptic curve group
T_X	Time stamp of an entity X

p, q	Large primes such that $q p-1$
g	Generator of a multiplicative subgroup with order q
a	Random number generated by MU for a session
b	Random number generated by FA for a session
c	Secret number fixed by HA
$E_X[\cdot]/D_X[\cdot]$	Symmetric encryption/decryption using secret key
$ES_X\{\cdot\}$	Asymmetric encryption using private key
$DP_X\{\cdot\}$	Asymmetric decryption using public key
$GS_X(\cdot)$	Signature generation using private key
$VP_X(\cdot)$	Signature verification using public key
$\oplus$	Exclusive-or (XOR) function
$h(\cdot)$	One-way hash function, $h: \{0, 1\}^* \rightarrow \{0, 1\}^l$
$\parallel$	Concatenation of two inputs
$=?$	Comparison of two inputs
$TR(\cdot)$	k -bits (length of SK) truncation from least significant bit of the input

Figure 1. Registration Phase of the Zhao et al.'s Scheme

Step A1: The MU inserts its smart card into the card reader and inputs its identity and password. Then the smart card computes $H' = h(ID_{MU} || h(PW_{MU} || N_{MU}))$ and checks whether it is equal to H . Next, the smart card generates a random number a and computes $A = aP$, $R_{AC} = aC$, $N = Q \oplus h(PW_{MU} || N_{MU})$, $DID_{MU} = ID_{MU} \oplus h(R_{AC})$, and $V_I = h(N || R_{AC} || ID_{HA} || A || C)$. Here the computation of aP denotes the scalar multiplication of point P on the cyclic group. Then the MU sends $\{A, DID_{MU}, C, V_I, ID_{HA}\}$ to the FA through a public wireless channel.

Figure 2. Authentication and Session Key Establishment Phase of the Zhao et al.'s Scheme

Step A2: After receiving an access request message, the FA generates a random number b and computes $B = bP$, $R_{BC} = bC$, $W_2 = E_{R_{BC}}[A, B, Cert_{FA}, V_1, DID_{MU}]$, and $V_2 = E_{S_{FA}}\{h(A, B, Cert_{FA}, V_1, DID_{MU})\}$. Here S_{FA} is a private key of the FA. Then, it sends $\{B, W_2, V_2\}$ to the HA.

Step A3: Upon receiving the message from the FA, the HA computes a common key $R_{BC} = cB$ and decrypts W_2 by using this key. Then, it verifies the FA's signature V_2 to authenticate the FA by using the certificate $Cert_{FA}$. Afterward, the HA computes $R_{AC} = cA$, $ID_{MU} = DID_{MU} \oplus h(R_{AC})$, and $V_1' = h(h(ID_{HA} || y) || R_{AC} || ID_{HA} || A || C)$. Then, to authenticate the MU, it checks whether V_1 is equal to V_1' . Next, the HA generates a random number d and computes $D = dP$, $G_{MU} = dB \oplus R_{AC}$, $W_1 = h(h(ID_{MU} || y) || dB || A || D || ID_{FA} || ID_{HA})$, $W_3 = E_{R_{BC}}[ID_{FA}, Cert_{HA}, G_{MU}, dA, A, B, D, W_1]$, and $V_3 = E_{S_{HA}}\{h(ID_{FA}, Cert_{HA}, G_{MU}, dA, A, B, D, W_1)\}$. Finally, the HA sends $\{W_3, V_3\}$ to the FA.

Step A4: After receiving the response message from the HA, the FA computes a common key $R_{BC} = cB$ and decrypts W_3 by using this key. Then, it verifies the HA's signature V_3 to authenticate the HA by using the certificate $Cert_{HA}$. After

authenticating the HA and the MU, the FA computes the session key $SK = h(bdA)$ and $W_4 = E_{SK}[W_1, D, ID_{FA}]$ and then sends $\{G_{MU}, W_4\}$ to the MU.

Step A5: The MU computes $dB = G_{MU} \oplus R_{AC}$ and decrypts $D_{SK}[W_4]$ by using the session key $SK = h(adB)$. Then it computes $W_1' = h(N//dB//A//D//ID_{FA}//ID_{HA})$ and compares it with W_1 . If they are equal, then the FA and the HA are authenticated. Further, the MU confirms that the SK is the common session key shared with the FA. Finally, the MU computes $Auth = h(W_1//adB)$ and sends it to the FA.

Step A6: When the FA receives the message $Auth$, it computes $Auth' = h(W_1//bdA)$ and compares it with $Auth$. If they are equal, then the FA verifies that the SK is the common session key shared with the MU.

4. Weaknesses and Inefficiencies of Zhao *et al.*'s Scheme

This section shows that Zhao *et al.*'s anonymous authentication scheme has the following weaknesses and inefficiencies:

4.1. Weaknesses Against the Replay Attack

In Zhao *et al.*'s scheme, suppose an attacker may intercept the login request message $\{A, DID_{MU}, C, V_1, ID_{HA}\}$ and send it to the FA next time. The FA and the HA accept this replay message for anonymous authentication and ensure that the attacker is a legal user. As a result, the attacker receives the response message $\{G_{MU}, W_4\}$ from the FA. Although the attacker cannot compute the session key shared with the FA because it lacks knowledge of the MU's random number a , it can impersonate the MU to access the FA. This replay attack obviously causes unnecessary communications and computational costs. Therefore, Zhao *et al.*'s scheme fails to protect against a strong replay attack.

In addition, it can be assumed that the attack can replay mass login messages to the FA at the same time. Then the FA and the HA should always process from Step A2 to Step A4 per the request message. They cannot detect the attacker's behavior among all access requests in this strong replay attack. Therefore, because the FA and the HA can exhaust their computational resources, the FA or HA in Zhao *et al.*'s scheme can become a victim by the denial of service (DoS) attack. Because the distributed DoS (DDoS) attack causes the FA or HA to sit down, this replay-based DoS attack can become an important threat in Zhao *et al.*'s scheme.

4.2. Pre-distribution of System Parameters

The cryptographic primitive such as the hash function or encryption does not need any extra system parameters. However, in the primitive such as the Diffie-Hellman key agreement or digital signature, which is based on public key cryptography, system parameters should be handed over to the other entity through the pre-distribution or transmission during the communication session. All entities in Zhao *et al.*'s scheme uses the scalar point P and elliptic curve system parameters such as the field prime and coefficients of the curve equation. However, no entity transmits these system parameters in all transactions. This means that a trusted third party at the top level is required to provide these system parameters. This party should generate these system parameters once and previously distribute them to all HAs and FAs. It is extremely inconvenient when a new FA or HA joins GLOMONET. Further, because all entities should compulsorily use the same system parameters, Zhao *et al.*'s scheme is rigid and impractical. Therefore, there is a need for a more flexible and diverse anonymous authentication scheme. Under the assumption that GLOMONET contains various HAs, it should at least consider that the HA may generate different system parameters with other HAs and store them in the smart card of its MU.

4.3. Inefficiencies from Unnecessary Encryptions

In Zhao et al.'s scheme, the FA has two encryptions for the message, and the HA has one. In addition, the MU, the FA, and the HA all have a decryption operation according to the encrypted message respectively. The encryption function is basically performed to provide message confidentiality. However, most messages used as an encryption input are transmitted through networks in their scheme. Further, the certificate of the FA or HA is generally open information.

For example, inputs of the encrypted output W_2 are A , B , $Cert_{FA}$, V_1 , and DID_{MU} . Unfortunately, these inputs are known to all entities, including malicious attackers. Therefore, the encryption of a known message is unnecessary with respect to the cryptographic service of confidentiality. Among input messages of an encryption, only the dA value is not revealed. Despite this fact, even if the dA value is opened, it does not matter to security. As a result, because there is no need to hide sending messages in Zhao et al.'s scheme, encryption and decryption operations that increase operational complexity are useless.

5. The Proposed Scheme

This section proposes a lightweight and robust anonymous authentication scheme for roaming services in GLOMONET. The design elements of this proposed scheme include computational efficiency and resistance to security threats. The HA chooses a multiplication group G and a generator $g \in G$ whose order is q . That is, q is the smallest positive integer satisfying $g^q \bmod p = 1$, where p and q are large primes. In addition, p is the modulus for operations in group G such as $q|p-1$. The HA first chooses a random secret number $c (< q)$ and computes $C = g^c \bmod p$. In addition, the HA has a private/public key pair S_{HA}/P_{HA} and the certificate $Cert_{HA}$ of its public key. The FA also has its private/public key pair and certificate.

5.1. Security Model in GLOMONET

To design a practical and secure anonymous authentication scheme, security functions of each entity are investigated. The MU subscribes to its HA as a client. In the registration step, the MU sends its identity and some related messages to the HA and receives a smart card including secret information and system parameters generated by the HA. Afterward, if the MU wants to access the foreign network by using the password and smart card, the HA anonymously authenticates the MU. The HA then informs the FA that the MU is a legal user. Here there is a need for a countermeasure to check replay messages. The use of a time stamp for filtering old messages is a potential solution.

Based on the public key infrastructure (PKI), the FA and the HA mutually authenticate by using certificates of their public key. In addition, the Diffie-Hellman key agreement technique is used to establish a session key between the MU and the FA and authenticate each other. The overall outline of the security model of the proposed scheme is shown in Figure 3. In this GLOMONET environment, there are various HAs and FAs, and the HA has its own system parameters. Therefore, the MU with system parameters of its HA must send them to the FA to access the foreign network.

The proposed scheme consists of five phases: (1) registration phase, (2) authentication and session key establishment phase, (3) password change phase, (4) update session key phase, and (5) authentication and session key establishment phase when the MU is located in its HN.

Figure 3. Security Model in GLOMONET

5.2. Registration Phase

If the MU wants to register to its HA, it must submit necessary information through a secure channel. After verifying that the MU is legal, the HA issues a temper-resistant smart card to the MU. Figure 4 details the registration phase.

Step R1: A new MU chooses its identity ID_{MU} and password PW_{MU} . Then the MU submits its identity ID_{MU} to its HA for registration over a secure channel.

Step R2: After receiving the identity ID_{MU} from the MU, the HA computes $R = h(y || ID_{HA} || ID_{MU})$, where y is the HA's secret master key. Then the HA stores the information $\{R, ID_{HA}, C, g, p\}$ in a temper-resistant smart card and issues the smart card to the MU through a secure channel.

Step R3: When receiving the smart card from the HA, the MU generates a large random number N_{MU} and computes $I = h(ID_{MU} || PW_{MU} || N_{MU})$ and $H = R \oplus I$. Here the choice space of ID_{MU} and PW_{MU} must be enough to resist a simultaneous guessing attack even when I and N_{MU} are revealed by a physical breach attack on the smart card. Then, the MU replaces R with H in the smart card. In addition, the smart card stores I and N_{MU} .

Figure 4. Registration Phase of the Proposed Scheme

5.3. Authentication and Session Key Establishment Phase

If the MU roams into a foreign network, it must authenticate the FA and prove its legality to the FA with the help of its HA. Figure 5 details this phase. The authentication and session key establishment phase between the MU and the FA is described as follows:

Step A1: The MU inserts the smart card into the card reader and enters its identity ID_{MU} and password PW_{MU} . After reading N_{MU} , the smart card computes $I' = h(ID_{MU} || PW_{MU} || N_{MU})$ and checks whether $I = I'$ by using the stored value I . If the checking holds, then the MU is verified to be a legitimate user. Otherwise, this phase is terminated. The smart card then generates a random number a and computes $A^a \text{ mod } p$, $K = C^a \text{ mod } p$, $P = ID_{MU} \oplus h(K || T_{MU})$, and $Q = H \oplus I \oplus h(A || K)$. Finally, the MU sends the necessary message $\{A, P, Q, g, p, ID_{HA}, T_{MU}\}$ to the FA over a wireless channel. Here, to avoid the user tracking attack, the length of ID_{MU} should be less than $h(K || T_{MU})$.

Step A2: After receiving the request message from the MU, the FA checks the time stamp T_{MU} to determine whether it is within the expected time interval. If not, the access

request is rejected immediately. Otherwise, the FA keeps the time stamp and the message pair for some time to check the replay attack. If the FA receives the same time stamp and message pairs during this time interval, it decides that the second message is a retransmitted one and discards it. Next, the FA generates a random number b and computes $B = g^b \text{ mod } p$. Then it makes a signature by using its private key S_{FA} such that $U = G_{S_{FA}}(A, B, P, Q, ID_{FA}, T_{FA})$. Finally, the FA sends $\{A, B, P, Q, U, T_{MU}, T_{FA}, ID_{FA}, Cert_{FA}\}$ to the HA.

Step A3: If the HA receives the message from the FA, it checks the time stamps T_{FA} and T_{MU} to determine whether they are within the expected time interval and keeps the time stamp and the message pair for some time to check the replay attack. Then the HA verifies the FA's signature U by using the certificate $Cert_{FA}$ for the FA's public key. If the signature is valid, then the FA is authenticated. Afterward, the HA computes $K' = A^c \text{ mod } p$, $ID_{MU} = P \oplus h(K' || T_{MU})$, and $V = h(y || ID_{HA} || ID_{MU})$ and then checks whether the value of $Q \oplus h(A || K')$ is equal to V . If it is valid, then the MU is authenticated. Then the HA stores A and B in D and E , respectively, and computes $Y = h(V || D || B || ID_{HA} || ID_{FA})$. Finally, the HA generates a signature by using its private key such that $Z = G_{S_{HA}}(Y, D, E, ID_{HA}, ID_{FA})$ and sends $\{Y, Z, D, E, ID_{HA}, Cert_{HA}\}$ to the FA.

Figure 5. Authentication and Session key establishment phase of the proposed scheme

Step A4: After receiving the message from the HA, the FA verifies the HA's signature Z by using the certificate $Cert_{HA}$ for the HA's public key. If it is valid, then the HA is authenticated. Then the FA checks D and E to determine whether they are the same as A and B , respectively. If they are valid, then the MU is authenticated. The FA then computes the session key $SK = TR(A^b \bmod p)$ and makes a message authentication code such that $W = h(SK || Y || D || B || ID_{FA})$. Finally, the FA sends $\{W, Y, D, B, ID_{HA}, ID_{FA}\}$ to the MU.

Step A5: Upon receiving the message from the FA, the MU checks that the received D is equal to A . Then it verifies the message authentication code Y generated by the HA. Then the MU computes the session key $SK = TR(B^a \bmod p)$ and verifies a message authentication code W generated by the FA. If it is valid, then the shared session key $SK = TR(B^a = g^{ab} \bmod p)$ is verified.

5.4. Password Change Phase

This phase occurs when the MU wants to change its password. There is no communication with a foreign network or its HA. The password change phase consists of the following steps:

Step P1: The MU inserts its smart card into the card reader and enters its identity ID_{MU} and old password PW_{MU}^{old} . The smart card computes $I' = h(ID_{MU} || PW_{MU}^{old} || N_{MU})$, and checks whether $I = I'$ by using the stored value I . If it holds, then the MU is verified to be a legitimate user. Otherwise, this phase terminates immediately.

Step P2: The MU generates a new random number N_{MU}^{new} and inputs a new password PW_{MU}^{new} . Then the smart card computes $I^{new} = h(ID_{MU} || PW_{MU}^{new} || N_{MU}^{new})$ and $H^{new} = H \oplus I \oplus I^{new}$. Finally, the smart card replaces old H , I , and N_{MU} values with new values of H^{new} , I^{new} , and N_{MU}^{new} , respectively.

5.5. Update Session Key Phase

The MU and the FA must renew the session key to ensure strong security when the MU is always within the same foreign network. The following processes are used to update the session key in the i -th session:

Step U1: The MU selects a random number a_i , computes $A_i = g^{a_i} \bmod p$, and sends A_i to the FA.

Step U2: After receiving A_i from the MU, the FA selects a random number b_i , computes a new session key $SK_i = TR(A_i^{b_i} \bmod p)$ and $B_i = g^{b_i} \bmod p$, and then sends $H_i = h(SK_i || SK_{i-1})$ and B_i to the MU.

Step U3: The MU computes a new session key $SK_i = TR(B_i^{a_i} \bmod p)$ and $H_i' = h(SK_i || SK_{i-1})$ and compares H_i with H_i' . If they are equal, then the MU verifies the session key. Otherwise, the MU aborts updating the session key.

5.6. Authentication and Session Key Establishment Phase between the MU and the HA

If the MU roams into its HN, it must directly authenticate the HA and prove its legality to the HA. Figure 6 provides a detailed description of this phase. The authentication and session key establishment phase when the MU is located in its HN is described as follows:

Step H1: The MU inserts the smart card into the card reader and enters its identity ID_{MU} and password PW_{MU} . After reading N_{MU} , the smart card computes $I' = h(ID_{MU} || PW_{MU} || N_{MU})$ and checks whether $I = I'$ by using the stored value I . If the checking holds, then the MU is verified to be a legitimate user. Otherwise, this phase is terminated. The smart card then generates a random number a and computes $A = g^a \bmod p$, $K = TR(C^a$

mod p), $P = ID_{MU} \oplus h(K||T_{MU})$, and $Q = H \oplus I \oplus h(A||K)$. Finally, the MU sends the necessary message $\{A, P, Q, g, p, ID_{HA}, T_{MU}\}$ to the HA over a wireless channel.

Step H2: If the HA receives the message from the MU, it checks the time stamp T_{MU} to determine whether they are within the expected time interval and keeps the time stamp and the message pair for some time to check the replay attack. The HA computes $K' = A^c \text{ mod } p$, $ID_{MU} = P \oplus h(K'||T_{MU})$, and $V = h(y||ID_{HA}||ID_{MU})$ and then checks whether the value of $Q \oplus h(A||K')$ is equal to V . If it is valid, then the MU is authenticated. Then the HA stores A and K' in D and SK , respectively, and computes $Y = h(SK||D||C||ID_{HA})$. Finally, it sends $\{Y, D, ID_{HA}\}$ to the MU.

Step H3: Upon receiving the message from the HA, the MU checks whether the received D is equal to A . Then it verifies the message authentication code Y generated by the HA by using the session key $SK = K$. If it is valid, then the shared session key $SK = TR(C^a = g^{ac} \text{ mod } p)$ is verified.

Figure 6. Authentication and Session Key Establishment between MU and HA

6. Security Analysis

This section analyzes the security of the proposed scheme according to security requirements for a secure GLOMONET environment and compares the scheme with existing schemes.

6.1. User Anonymity and Untraceability

In the proposed scheme, the identity of MU, ID_{MU} , is submitted to the HA over a secure channel in the registration phase. Because only the HA knows the identity of the MU at that time, an attacker cannot obtain it. Assume that any attacker eavesdrops on the message $\{A, P, Q, g, p, ID_{HA}, T_{MU}\}$ transmitted between the MU and the FA. However, the attacker cannot derive the real identity of the MU without knowing the common secret information K between the MU and the HA. In addition, because the transmitted messages A, P and Q are dynamically changed in each session, the attacker cannot trace the MU's moving history and current location. Therefore, the proposed scheme can provide user anonymity and untraceability for the MU.

6.2. Impersonation Attack

To impersonate as a legal MU, an attacker with some arbitrary ID_{MU} must cheat the HA. In the proposed scheme, the HA authenticates the MU by comparing the value $V = h(y||ID_{HA}||ID_{MU})$ with $Q \oplus h(A||K)$. An attacker can arbitrary compute A and K by using its random number a before sending the request message to the FA. However, the attacker does not know the MU's password PW_{MU} and thus cannot compute $I = h(ID_{MU}||PW_{MU}||N_{MU})$ and $Q \oplus h(A||K) = H \oplus I$. Therefore, an attacker without knowledge of the MU's password cannot cheat the HA by pretending to be as a legal user. The attacker cannot impersonate as an HA (resp. FA) because messages generated by the attacker without knowledge of the private key are detected by the mutual authentication process of the FA (resp. HA). As a result, the proposed scheme can prevent these impersonation attacks.

6.3. Replay Attack

The proposed scheme adopts the time stamp to prevent the replay attack. If an attacker sends the previous session messages $\{A, P, Q, g, p, ID_{HA}, T_{MU}\}$ to the FA, the FA checks whether the MU's time stamp is within the expected time interval. It is the first countermeasure against the replay attack. Nevertheless, an attack can send the previous message $\{A, P, Q, g, p, ID_{HA}, T_{MU}^c\}$ only by changing the old time stamp T_{MU} to the current one T_{MU}^c . However, the HA can detect the invalidity of time by computing $ID_{MU}^* = P \oplus h(K' || T_{MU}^c)$ and $V^* = h(y||ID_{HA} || ID_{MU}^*)$ and checking whether V^* is not equal to $Q \oplus h(A||K')$. Actually, both ID_{MU}^* and V^* computed by the HA are incorrect. Consequently, an attacker cannot modify the MU's time stamp without knowing the secret common information K and the identity of the MU. In addition, the time stamp of the FA, T_{FA} , can be authenticated to the HA by using the FA's signature U . Therefore, the proposed scheme can prevent the replay attack by using the time stamp.

6.4. Perfect Forward Secrecy

Perfect forward secrecy means that even if an attacker compromises the previous session key between the MU and the FA, it cannot derive a new session key. In the proposed scheme, because the session key $SK = g^{ab} \bmod p$ is computed using one-time random numbers a and b in each session, an attacker cannot retrieve the session key from transmitted messages $A = g^a \bmod p$ and $B = g^b \bmod p$ based on the security of the DLP and the CDHP. Because two session keys are always generated independently, knowledge of the previous session key $SK^* = g^{a^*b^*} \bmod p$ and transmitted messages does not help in deriving the current session key $SK = g^{ab} \bmod p$ and vice versa. Therefore, the proposed scheme can achieve perfect forward secrecy.

6.5. Off-line Password Guessing Attack

In the proposed scheme, even when the smart card has temper-resistant protection, it is assumed that the MU's smart card is stolen by an attacker. In addition, the attacker can obtain H, I, ID_{HA}, C, g, p , and N_{MU} from the MU's stolen smart card by using strong physical attacks. After guessing the MU's password, the attacker tries to verify that the guessed password is correct or find ID_{MU} by using the aforementioned collected information. The attacker tries to compute $h(ID_{MU} || PW_{MU}^{guessed} || N_{MU})$ and compare it with I . However, this is not possible because ID_{MU} is kept only by the MU and the HA. In addition, simultaneous off-line guessing for both the password and identity of the MU is really a hard problem for the attacker. As a result, the proposed scheme is secure against the off-line password guessing attack.

6.6. Insider Attack

If an insider of the HA obtains the MU's password, it can try to impersonate as a legal MU to access the FA. In the registration and authentication phases, the HA knows only the identity of the MU, ID_{MU} . However, the insider cannot derive or guess the MU's password without N_{MU} . In addition, the MU can change the password PW_{MU} and the random number N_{MU} without the help of the HA in the password change phase. As a result, the proposed scheme can withstand the insider attack.

6.7. Stolen-Verifier Attack

The HA and the FA do not maintain any verifier tables and secret key databases. Therefore, the stolen-verifier attack does not apply to the proposed scheme.

6.8. Local Password Attack

In the authentication and key establishment phase, if the validity of the user's identity and password is not checked before accessing the FA, then an attacker with a stolen smart card can impersonate a legal user in all transactions. Based on this fact, the proposed scheme is designed to avoid any unauthorized use for mobile devices by verifying the local password. Table 2 compares the proposed scheme with some recently proposed schemes in terms of security properties and functionalities. The proposed scheme satisfies almost all security requirements of GLOMONET.

Table 2. Comparison of Security and Functionality

Security and functionality	Proposed scheme	Zhao et al. [10]	Xie et al. [12]	Das [13]	He et al. [4]
User anonymity	O	O	O	O	X
Impersonation attack	O	O	O	O	O
Strong replay attack	O	X	O	O	O
Perfect forward secrecy	O	O	O	O	X
Off-line password guessing attack	O	O	O	O	O
Insider attack	O	O	O	O	O
Stolen-Verifier attack	O	O	X	O	O
Local password attack	O	O	X	O	O
Authentication when MU is located in HN	O	O	X	X	O
No pre-distribution of system parameters	O	X	X	X	O

Note : O : secure or support × : insecure or not support

7. Performance Analysis

This section compares the performance of the proposed scheme with that of some existing schemes. Here the analysis focuses on the computational cost of the authentication and key establishment phase because this phase is the main part of the anonymous authentication scheme. Table 3 provides the comparison results for the total computational cost. The time complexity of the following primitives is compared in this table: (1) modular exponentiation, (2) scalar multiplication, (3) signature generation, (4) signature verification, (5) symmetric encryption, (6) symmetric decryption, (7) asymmetric encryption, (8) asymmetric decryption, and (9) hash operations.

Table 3. Comparison of the Computational Cost

Primitives	Entities	Proposed scheme	Zhao et al. [10]	Xie et al. [12]	Das [13]	He et al. [4]

Modular exponentiation	MU	3	-	3	4	-
	FA	2	-	2	5	-
	HA	1	-	2	3	-
Scalar multiplication	MU	-	3	-	-	-
	FA	-	3	-	-	-
	HA	-	4	-	-	-
Signature generation	MU	-	-	-	-	-
	FA	1	1	-	1	1
	HA	1	1	-	1	1
Signature verification	MU	-	-	-	-	-
	FA	1	1	-	1	1
	HA	1	1	-	1	1
Symmetric encryption	MU	-	-	1	3	1
	FA	-	2	1	2	1
	HA	-	1	1	1	-
Symmetric decryption	MU	-	1	1	1	1
	FA	-	1	-	2	-
	HA	-	1	3	4	2
Asymmetric encryption	MU	-	-	-	-	-
	FA	-	-	-	-	-
	HA	-	-	-	-	1
Asymmetric decryption	MU	-	-	-	-	-
	FA	-	-	-	-	1
	HA	-	-	-	-	-
Hash operation	MU	5	7	4	3	10
	FA	1	2	2	2	4
	HA	4	4	1	5	4

As shown in Table 3, in the proposed scheme, the MU requires three modular exponentiations and five hash operations. As an example of the parameter length for security complexity, a 1024-bit prime p and a 160-bit exponent a can be adopted. In addition, two of three modular exponentiations can be pre-computed before starting the real session. The FA requires two exponentiations to establish the session key, generates one signature, verifies one signature, and performs one hash operation. The HA requires one exponentiation to authenticate the MU, generates one signature, verifies one signature, and performs four hash operations. It is easy to see that the proposed scheme is more efficient than existing schemes.

The proposed scheme uses no encryption and decryption primitives. There is a need to consider that the main cryptographic services of these schemes are intrinsically anonymous authentication and session key establishment between the MU and the FA. Therefore, in this phase, the important security functions are user authentication and message integrity between entities. Confidentiality can be achieved after establishing a common session key. As a result, encryption and decryption processing can be avoided in the proposed phase. Therefore, the proposed scheme is designed using only modular exponentiation, signature generation, signature verification, and hash functions.

Indeed, for the key exchange between two entities in the proposed scheme, the elliptic curve Diffie-Hellman protocol can be adopted instead of the DLP-based Diffie-Hellman protocol. However, in the elliptic curve Diffie-Hellman protocol, the HA generates elliptic curve domain parameters, the scalar point P , and its public key $C = cP$ and stores them in the smart card of the MU. Then the MU must always send these parameters with other messages to the FA in the authentication and session key establishment phase.

8. Conclusions

This paper shows that Zhao *et al.*'s anonymous authentication scheme for roaming services in GLOMONET has weaknesses against a strong replay attack and is impractical for requiring the pre-distribution of system parameters. In addition, their scheme has unnecessary encryption/decryption operations that can increase of communications and computational costs. To overcome these weaknesses and inefficiencies, this paper proposes a novel anonymous authentication scheme that satisfies most security requirements and is suitable for low-power and resource-limited mobile devices based on its lightweight design.

References

- [1] S. Suzukiz and K. Nakada, "An authentication technique based on distributed security management for the global mobility network", IEEE Journal Selected Areas in Communications, vol. 15, no. 8, (1997), pp. 1608-1617.
- [2] C. Lee, M. Hwang, and I. Liao, "Security enhancement on a new authentication scheme with anonymity for wireless environments", IEEE Transactions on Industrial Electronics, vol. 53, no. 5, (2006), pp. 1683-1686.
- [3] C. Wu, W. Lee, and W. Tsaur, "A secure authentication scheme with anonymity for wireless environments", IEEE Communications Letters, vol. 12, no. 10, (2008), pp. 722-723.
- [4] D. He, M. Ma, Y. Zhang, C. Chen, and J. Bu, "A strong user authentication scheme with smart cards for wireless communications", Computer Communications, vol. 34, no. 3, (2011), pp. 367-374.
- [5] J. Zhu and J. Ma, "A new authentication scheme with anonymity for wireless environments", IEEE Transactions on IEEE Communication Letter, vol. 13, no. 7, (2004), pp. 1118-1123.
- [6] C. Chang, C. Lee, and Y. Chiu, "Enhanced authentication scheme with anonymity for roaming service in global mobility networks", Computer Communications, vol. 32, no. 4, (2009), pp. 611-618.
- [7] T. Youn, Y. Park, and J. Lim, "Weaknesses in an anonymous authentication scheme for roaming service in global mobility networks", IEEE Communications Letters, vol. 13, no. 7, (2009), pp. 471-473.
- [8] C. Li and C. Lee, "A novel user authentication and privacy preserving scheme with smart cards for wireless communications", vol. 55, no. 1-2, (2012), pp. 35-44.
- [9] H. Mun, K. Han, Y. Lee, C. Yeun, and H. Choi, "Enhanced secure anonymous authentication scheme for roaming service in global mobility networks", Mathematical and Computer Modelling, vol. 55, no. 1-2, (2012), pp. 214-222.
- [10] D. Zhao, H. Peng, L. Li, and Y. Yang, "A secure and effective anonymous authentication scheme for roaming service in global mobility networks", Wireless Personal Communications, vol. 78, no. 1, (2014), pp. 247-269.
- [11] Y. Chen, S. Chuang, L. Yeh, and J. Huang, "A practical authentication protocol with anonymity for wireless access networks", Wireless Communications and Mobile Computing, vol. 11, no. 10, (2011), pp. 1366-1375.
- [12] Q. Xie, B. Hu, X. Tan, M. Bao, and X. Yu, "Robust anonymous two-factor authentication scheme for roaming service in global mobility network", Wireless Personal Communications, vol. 74, no. 2, (2014), pp. 601-614.
- [13] A. Das, "A secure and effective user authentication and privacy preserving protocol with smart cards for wireless communications", Networking Science, vol. 2, no. 1-2, (2013), pp. 12-17.
- [14] F. Wen, W. Susilo, and G. Yang, "A secure and effective anonymous user authentication scheme for roaming service in global mobility network", Wireless Personal Communications, vol. 73, no. 3, (2013), pp. 993-1004.
- [15] W. Jeon, Y. Lee, and D. Won, "An efficient user authentication scheme with smart cards for wireless communications", International Journal of Security and Its Applications, vol. 7, no. 4, (2013), pp. 1-15.
- [16] Z. Tan, "Cryptanalysis and improvements of an anonymous authentication scheme for roaming service in global mobility networks", International Journal of Security and Its Applications, vol. 7, no. 6, (2013), pp. 335-344.
- [17] B. Hu, Q. Xie, M. Bao, and N. Dong, "Improvement of user authentication protocol with anonymity for wireless communications", Kuwait Journal of Science, vol. 41, no. 1, (2014), pp. 155-169.
- [18] W. Stallings, Cryptography and Network Security: Principles and Practices, 3rd ed. Prentice Hall, (2002)
- [19] W. Diffie and M. Hellman, "New directions in cryptography", IEEE Transactions on Information Theory, vol. 22, no. 6, (1976), pp. 644-654.
- [20] N. Koblitz, "Elliptic curve cryptosystem", Journal of Mathematics of Computation, vol. 48, no. 177, (1987), pp. 203-209.

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