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A secure effective dynamic group password-based authenticated key agreement scheme for the integrated EPR information system

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Abstract With the rapid growth of the Internet, a lot of electronic patient records (EPRs) have been developed for e-medicine systems. The security and privacy issues of EPRs are important for the patients in order to understand how the hospitals control the use of their personal information, such as name, address, e-mail, medical records, etc. of a particular patient. Recently, Lee et al. proposed a simple group password-based authenticated key agreement protocol for the integrated EPR information system (SGPAKE). However, in this paper, we show that Lee et al.'s protocol is vulnerable to the off-line weak password guessing attack and as a result, their scheme does not provide users' privacy. To withstand this security weakness found in Lee et al.'s scheme, we aim to propose an effective dynamic group password-based authenticated key exchange scheme for the integrated EPR information system, which retains the original merits of Lee et al.'s scheme. Through the informal and formal security analysis, we show that our scheme provides users' privacy, perfect forward security and known-key security, and also protects online and offline password guessing attacks. Furthermore, our scheme efficiently supports the dynamic group password-based authenticated key agreement for the integrated EPR information system. In addition, we simulate our scheme for the formal security verification using the widely-accepted AVISPA

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(Automated Validation of Internet Security Protocols and Applications) tool and show that our scheme is secure against passive and active attacks.

1. Introduction

In an integrated EPR (electronic patient record) information system of all the patients, the medical institutions and the academia with most of the patients' information in details for them, can make the corrective decisions and clinical decisions in order to maintain and analyze patients' health. In such systems, the illegal access needs to be avoided as well as the information from theft during transmission over the insecure Internet needs to be prevented.

A dynamic group key agreement protocol provides the mechanisms to process member addition and deletion. Several dynamic group key agreement protocols have been proposed in the literature. We can divide the group key agreement protocols into two categories (Lee et al., 2013). The first one is the group key agreement protocols with public key. For example, key agreement protocols proposed by Tzeng and Tzeng (2000), Tzeng (2002), Boyd and Nieto (2003), Kim et al. (2004), Lee et al. (2006), and Jeong and Lee (2007) employ the public key infrastructure (PKI) and provide higher security. However, they are required to maintain the complex and heavy public key systems and users must hold extra storage for keeping public/private key pairs. The second one is the group password-based key agreement protocols (GPKE) without public key. For example, key agreement protocols of Lee et al. (2004), Abdalla et al. (2006), and Dutta and Barua (2006) provide the same password to all communicating parties. That is, each user does not have his/her own private password, and thus, the user cannot have his/her privacy. However, Zhang et al. (2012) showed that Dutta and Barua's scheme (Dutta and Barua, 2006) is insecure, where their scheme does not satisfy the key independence property (Steiner et al., 2000) and any two malicious users whose logic indexes are not adjacent in the former execution of the protocol may mount a replay attack in new protocol executions. Hence, these password-based approaches are not much suitable for many practical scenarios (Lee et al., 2013).

Boyd and Nieto (2003) described the first conference key agreement protocol, which can be completed in a single round. However, their scheme lacks forward secrecy property. By the forward secrecy property, we mean that when a node (user) leaves the network, it must not read any future messages after its departure. Kim et al. (2004) proposed an efficient and secure constant-round authenticated key agreement protocol (AGKE) for dynamic groups in the random oracle model. Dutta and Barua (2006) proposed a variant of Kim et al.'s scheme (Kim et al., 2004). Dutta–Barua's scheme makes use of the ideal-cipher model, instead of a simple mask, and they claimed that their scheme is secure against dictionary attacks. Unfortunately, their scheme contains another source of redundancy that can be exploited by an attacker (Abdalla et al., 2006). In 2006, Abdalla et al. (2006) proposed the first provably-secure password-based constant-round group key exchange protocol. It is provably-secure in the random-oracle and ideal-cipher models, which makes use of the decisional Diffie–Hellman problem assumption.

Recently, Lee et al. (2013) have proposed a simple group password-based authenticated key protocol without the server's public key, called the SGPAKE protocol, for the integrated EPR information system. Their scheme is based on Abdalla and Pointcheval's scheme (Abdalla and Pointcheval, 2005). Lee et al.'s SGPAKE protocol does not use any long-term key or public-key system. Lee et al. (2013) claimed that SGPAKE protocol provides each user a unique private weak password and resists password-guessing attack, and thus their scheme provides user privacy and data privacy. However, in this paper, we show that any user U_i in a group S_n can derive the private password of the user U_{i-1} by setting the off-line password guessing attack, so that it does not provide the user's privacy. We aim to propose an improvement on Lee et al.'s SGPAKE protocol while retaining the original merits of Lee et al.'s scheme. Through the formal and informal security analysis, we show that our improved scheme provides user's privacy and perfect forward security, and also resists the offline password guessing attack.

The remainder of this paper is organized as follows. In Section 2, we provide the properties of the one-way hash function, discrete logarithm problem and group Diffie–Hellman problem. In Sections 3 and 4, we review Lee et al.'s SGPAKE protocol and then discuss the security flaws of Lee et al.'s SGPAKE protocol, respectively. We explain our improved scheme in Section 5. In Section 6, we provide the security of our improved scheme. Through the informal and formal security analysis, we show that our improved scheme is provably secure against an adversary for protecting the user's privacy and perfect forward security. In Section 7, we simulate our scheme for the formal security verification using the widely-accepted AVISPA (Automated Validation of Internet Security Protocols and Applications) tool and show that our scheme is secure. In Section 8, we compare the performances of our scheme with other related existing schemes. Finally, we conclude the paper in Section 9.

2. Mathematical preliminaries

In this section, we discuss the properties of the one-way hash function, discrete logarithm problem and group Diffie–Hellman problem, which are useful for describing Lee et al.'s SGPAKE protocol (Lee et al., 2013) and its security analysis as well as our improved scheme.

2.1. One-way hash function

A one-way collision-resistant hash function $h : \{0,1\}^* \rightarrow \{0,1\}^n$ is a deterministic algorithm (Sarkar, 2010; Stinson, 2006) that takes an input as an arbitrary length binary string $x \in \{0,1\}^*$ and outputs a binary string

$h(x) \in \{0,1\}^n$ of fixed-length n. The formalization of an adversary $\mathcal{A}$'s advantage in finding collision is given as follows

$$Adv_{\mathcal{A}}^{HASH}(t) = Pr[(x,x') \Leftarrow_R \mathcal{A} : x = x' \quad \text{and} \quad h(x) = h(x')],$$

where $Pr[E]$ denotes the probability of an event E in a random experiment, and $(x,x') \Leftarrow_R \mathcal{A}$ denotes the pair (x,x') is selected randomly by $\mathcal{A}$. In this case, the adversary $\mathcal{A}$ is allowed to be probabilistic and the probability in the advantage is computed over the random choices made by the adversary $\mathcal{A}$ with the execution time t. The hash function $h(\cdot)$ is said to be collision-resistant if $Adv_{\mathcal{A}}^{HASH}(t) \leqslant \epsilon$, for any sufficiently small $\epsilon > 0$.

An example of a secure one-way function is SHA-1 (Secure Hash Standard, 2010). One of the fundamental properties of a secure one-way hash function is that its outputs are very sensitive to small perturbations in inputs (Das, 2011). Recently proposed hash algorithm, Quark (Aumasson et al., 2010) is an efficient hash function than SHA-1. However, at present, the National Institute of Standards and Technology (NIST) does not recommend SHA-1 for top secret documents anymore. In 2011, Manuel showed that SHA-1 is insecure against collision attacks (Manuel, 2011). In this paper, as in Das and Goswami (2013) and Das et al. (2013), we can use SHA-2 as the secure one-way hash function for achieving top security. However, we use only 160-bits from the hash digest output of SHA-2 in Lee et al.'s SGPAKE scheme and our improved scheme.

2.2. Discrete logarithm problem (Das, 2013; Das et al., 2012)

Given an element g in a finite group G whose order is n, that is, $n = \#G_g$ (G_g is the subgroup of G generated by g) and another element y in G_g. The problem is to find the smallest non-negative integer x such that $g^x = y$. In this problem, known as the discrete logarithm problem (DLP), it is relatively easy to calculate discrete exponentiation $y = g^x \pmod p$ given g, x and n using the repeated square-and-multiply algorithm (Stallings, 2003), but it is computationally infeasible to determine x given y, g and n, when n is large. The formal definition of DLP is given in Definition 1 (Section 6.3).

2.3. Group Diffie–Hellman problem (Bresson et al., 2003)

Let G be a cyclic group, whose order be a prime n, that is, $\#G = n$. Let g be a generator of G. For a given set of values $g^{\Pi x_i}$ for some choice of x_i from the set $\{1,2,\ldots,n\}$, computing the common group Diffie–Hellman secret $g^{x_1 x_2 \ldots x_n}$ is computationally infeasible, when n is large. The formal definition of the group Diffie–Hellman problem can be found in Bresson et al. (2003).

3. Review of Lee et al.'s SGPAKE protocol

In this section, we briefly review the recently proposed Lee et al.'s SGPAKE protocol (Lee et al., 2013) in order to show the cryptanalysis on their scheme.

Lee et al.'s scheme consists of three phases, namely, the user registration phase, authenticated key exchange phase and password change phase. Each user needs to remember his/her weak private password, which is shared with a trusted server S. For describing Lee et al.'s scheme, we use the notations listed in Table 1. Assume that U_i, $(i = 1,2,\ldots,n)$ are n communicating parties, S is the trusted integrated EPR information system server. G_g is a multiplicative group generated by the generator g, p is a large prime, and M, N are large numbers, which are made public. $Z_p^* = \{1,2,3,\ldots,p-1\}$ is the set of all positive integers less than p and relatively prime to p. In other words, $Z_p^* = \{a | 0 < a < n, \gcd(a,n) = 1\}$, where $\gcd(x,y)$ denotes the greatest common divisor (gcd) of two integers x and y, and can be calculated efficiently using the repeated applications of the Euclid's division algorithm (Stallings, 2003).

3.1. User registration phase

In the user registration phase, a user needs to register to the server S before accessing the services from S. For registering, each new user U_i needs to select his/her chosen random nonce x_i. After that the user U_i sends this nonce x_i to the server S via a secure channel.

3.2. Authenticated key exchange phase

This phase consists of the following steps::

Step 1. $U_i \rightarrow S : m_1 = \{g^{x_i} M^{pw_i}\}$

- User U_i chooses a private weak password pw_i, which is shared with the trusted server S.
- User U_i computes g^{x_i} and $g^{x_i} M^{pw_i}$, using the selected random nonce x_i, chosen password pw_i and public key M of U_i in the user registration phase.
- User U_i then sends the message $\langle m_1 \rangle$ to the server S via a public channel, where $m_1 = \{g^{x_i} M^{pw_i}\}$.

Step 2. $S \rightarrow U_i : m_2 = \{g^{y_i} N^{pw_i}, E_{K_i}[S_n, K_{i-1}, K_i']\}$

- After receiving the message $\langle m_1 \rangle$ from the user U_i in Step 1, the server S chooses a random nonce y_i.
- Server S then computes g^{y_i}, $g^{y_i} N^{pw_i}$, $g^{x_i} = \frac{g^{x_i} M^{pw_i}}{M^{pw_i}}$, $K_{i-1} \equiv (g^{x_{i-1}})^{y_{i-1}} \pmod p$ and $K_i' \equiv (g^{x_{i+1}})^{y_i} \pmod p$, for $i = 1,2,\ldots,n$. Note that N is the public key of S.
- After that the server S encrypts the information (S_n, K_{i-1}, K_i') with the key K_i as $E_{K_i}[S_n, K_{i-1}, K_i']$, where $K_i = (g^{x_i})^{y_i} \pmod p$.
- Finally, the server S sends the message $\langle m_2 \rangle$ to the user U_i via a public channel, where $m_2 = \{g^{y_i} N^{pw_i}, E_{K_i}[S_n, K_{i-1}, K_i']\}$.

Step 3. $U_i \rightarrow^* : m_3 = \{X_i\}$

- After receiving the message $\langle m_2 \rangle$ in Step 2 from the server S, the user U_i computes the key $K_i = \left(\frac{g^{y_i} N^{pw_i}}{N^{pw_i}}\right)^{x_i} = g^{x_i y_i} \pmod p$, and then obtains the information K_{i-1} and K_i' by decrypting $E_{K_i}[S_n, K_{i-1}, K_i']$ with key K_i as $(S_n, K_{i-1}, K_i') = D_{K_i}[E_{K_i}[S_n, K_{i-1}, K_i']]$.
- If the user U_i successfully verifies $E_{K_i}[S_n, K_{i-1}, K_i']$, he/she computes $Z_i = (K_{i-1})^{x_i} \equiv g^{x_{i-1} y_{i-1} x_i} \pmod p$, $Z_{i+1} = (K_i')^{x_i} \equiv g^{x_i y_i x_{i+1}} \pmod p$ and $X_i = \frac{Z_{i+1}}{Z_i} = \frac{g^{x_i y_i x_{i+1}}}{g^{x_{i-1} y_{i-1} x_i}}$.

Table 1 Notations used in this paper.

Symbol	Description
S	Trusted integrated EPR information system server
U_i	A communicating user
ID_i	Identity of the user U_i
pw_i	The private password of the user U_i
ek_i	Symmetric encryption key of the user U_i
S_n	A dynamic group of n members
$H(\cdot)$	Secure one-way collision-resistant hash function
p	A large prime
g	A generator in group Z_p^*
M, N	Public keys
$E_K(\cdot)/D_K(\cdot)$	Symmetric encryption/decryption using the key K
$A \rightarrow B : X$	Entity A sends a message X to entity B via a public channel
C_1, C_2	Data C_1 is concatenated with data C_2

- Finally, the user U_i broadcasts the message $\langle m_3 \rangle$, where $m_3 = \{X_i\}$, to its group members in S_n via a public channel.

Step 4. $U_i \rightarrow^* : m_4 = \{Auth_{i1}, Auth_{i2}\}$

- After receiving the message $\langle m_3 \rangle$ in Step 3, the user U_i computes the secret value $sk_i = Z_i^n \times X_{i+1}^{n-1} \times X_{i+2}^{n-2} \times \cdots \times X_1^{i+n-1} = g^{x_1y_1x_2+x_2y_2x_3+\cdots+x_ny_nx_1} \pmod p$.
- U_i computes the key conformation signatures $(Auth_{i1}, Auth_{i2})$, where $Auth_{i1} = H(S_n, sk_i, U_i)$ and $Auth_{i2} = H(S_n, K_i')$.
- U_i then broadcasts the message $\langle m_4 \rangle$, where $m_4 = \{Auth_{i1}, Auth_{i2}\}$, via a public channel.
- Finally, U_i authenticates another user U_j by verifying $Auth_{j1}$, for $i \neq j$, and computes the common session key SK as $SK = H(S_n, sk_i)$. At the same time, the server S also authenticates each user U_i by verifying $Auth_{i2}$. As a result, by verifying $Auth_{i1}$ the mutual authentication among n users in a group S_n is achieved. On the other hand, by verifying $Auth_{i2}$ the server S performs the mutual authentication between the server S and n users in the group S_n.

3.3. Password change phase

If a legitimate user U_i wants to change his/her password pw_i, he/she sends his/her identity ID_i, the old password pw_i and the new password pw_i' to the integrated EPR information system S via a secure channel. The server S then checks the validity of ID_i and the old password pw_i. If these are valid, S updates pw_i with the new password pw_i'.

The summary of message exchanges during the user registration, authenticated key exchange and password change phases of Lee et al.'s scheme is shown in Table 2.

4. Cryptanalysis on Lee et al.'s SGPAKE protocol

In this section, we show that Lee et al.'s SGPAKE protocol is insecure against the offline password guessing attacks.

Lee et al. claimed that their scheme can provide each user with a private weak password and resist the password-guessing attacks. As a result, Lee et al.'s scheme should provide data privacy and user's privacy. However, we show that any user U_i in a group S_n can derive the password pw_{i-1} of another user U_{i-1} in that group S_n through the off-line password-guessing attacks. Thus, we show that Lee et al.'s SGPAKE scheme does not provide the user's privacy. A user U_i, being an attacker in a group S_n, can obtain the password pw_{i-1} of another user U_{i-1} in that group S_n using the following steps:

Step 1. The user U_i computes the key K_i as $K_i = \left(\frac{g^{y_i} N^{pw_i}}{N^{pw_i}}\right)^{x_i} = g^{x_iy_i} \pmod p$ and then obtains K_{i-1} and K_i' by decrypting $E_{K_i}[S_n, K_{i-1}, K_i']$ with key K_i as $(S_n, K_{i-1}, K_i') = D_{K_i}[E_{K_i}[S_n, K_{i-1}, K_i']]$.

Step 2. The user U_i obtains K_{i-2} and K_{i-1}' by decrypting $E_{K_{i-1}}[S_n, K_{i-2}, K_{i-1}']$ with the derived key K_{i-1} in Step 1 and then verifies the validity of K_{i-1}' using $Auth_{(i-1)2}$.

Step 3. The user U_i computes $g^{y_{i-1}}$ as $g^{y_{i-1}} = (K_{i-1}')^{x_i^{-1}} \pmod p = (g^{x_iy_{i-1}})^{x_i^{-1}} \pmod p$, where $x_i^{-1} \pmod p$ is computed efficiently using the extended Euclid's algorithm (Stallings, 2003).

Step 4. The user U_i then computes $N^{pw_{i-1}}$ as $N^{pw_{i-1}} = \frac{g^{y_{i-1}} N^{pw_{i-1}}}{g^{y_{i-1}}} \pmod p$ from the message $\langle m_2 \rangle$ of the userU_{i-1}.

Step 5. Note that the user U_{i-1}'s private password pw_{i-1} is a weak password. A user U_i can set up the off-line password-guessing attack to correctly obtain the private password pw_{i-1}' of the user U_{i-1} such that $N^{pw_{i-1}'} = N^{pw_{i-1}}$ iterating all possible choices of pw_{i-1}. This attack has the following steps:

Step 5.1. U_i selects a guessed password pw_{i-1}' for the user U_{i-1}.

Step 5.2. Knowing the public information N of the server S, U_i computes the value $N^{pw_{i-1}'}$.

Step 5.3. U_i compares the computed value $N^{pw_{i-1}'}$ with the derived value $N^{pw_{i-1}}$.

Step 5.4. If there is a match in Step 5.3, it indicates that the correct guess of the user U_{i-1}'s password pw_{i-1}. Otherwise, U_i repeats from Step 5.1.

As a result, the user U_i, being an insider attacker, can succeed to guess the low-entropy password pw_{i-1} of the user U_{i-1} in his/her own group S_n.

Table 2 Summary of message exchanges during the user registration, authenticated key exchange and password change phases of Lee et al.'s scheme (Lee et al., 2013).

Registration phase
$U_i \rightarrow S : pw_i, x_i$
(via a secure channel)

Authenticated key exchange phase
$U_i \rightarrow S : m_1 = \{g^{x_i} M^{pw_i}\}$
$S \rightarrow U_i : m_2 = \{g^{y_i} N^{pw_i}, E_{K_i}[S_n, K_{i-1}, K_i']\}$
$U_i \rightarrow^* : m_3 = \{X_i\}$
$U_i \rightarrow^* : m_4 = \{Auth_{i1}, Auth_{i2}\}$

Password change phase
$U_i \rightarrow S : ID_i, pw_i, pw_i'$
(via a secure channel)

5. The improved scheme

In this section, we first describe the main motivation behind our improved scheme. We then give a threat model under which our scheme is analyzed. Finally, we discuss the various phases related to our improved scheme.

5.1. Motivation

We have shown that any user U_i in a group S_n can derive the password pw_{i-1} of another user U_{i-1} in that group, S_n through the off-line password-guessing attack. Thus, Lee et al.'s SGPAKE scheme does not provide the user's privacy. Hence, we feel that there is a need to propose an improvement of Lee et al.'s scheme to withstand the security flaw found in Lee et al.'s SGPAKE scheme, while retaining the original merits of Lee et al.'s SGPAKE scheme. Through the formal and informal security analysis, we show that our improved scheme provides user's privacy and perfect forward security, and resists the offline password guessing attack. We also show that our scheme is efficient as compared to Lee et al.'s SGPAKE scheme and other related existing schemes.

5.2. Threat model

As in Das and Goswami (2013), we use the Dolev–Yao threat model (Dolev and Yao, 1983) in our improved scheme in which two communicating parties communicate over an insecure channel. Any adversary (attacker or intruder) can then eavesdrop the transmitted messages over the public insecure channel and he/she can modify, delete or change the contents of the transmitted messages. We adopt the similar threat model for our scheme, since the channel is insecure and the end-points (users and server) cannot in general be trustworthy.

5.3. Description of our improved scheme

Our scheme consists of three phases, namely, the user registration phase, the authenticated key exchange phase and the password change phase. As in Lee et al.'s protocol, each user also needs to only remember his/her weak password shared with a trusted server S. However, even if the password of a user is weak, our scheme resists the offline password guessing attack as compared to Lee et al.'s scheme. For describing our scheme, we also use the notations listed in Table 1. We assume that U_i, $(i = 1, 2, \ldots, n)$, are n communicating parties and S is the trusted integrated EPR information system server. G_g is a multiplicative group generated by the generator g, p is a large prime so that it is intractable to a discrete logarithm, and M, N are large public keys, which are made public, and $Z_p^* = \{1, 2, 3, \ldots, p-1\}$.

We describe the user registration phase, the authenticated key exchange phase and the password change phase in detail in the following subsections.

5.3.1. User registration phase

As in Lee et al.'s scheme, in our proposed improved scheme a user U_i first needs to register to the trusted server S before accessing the services from S. For registering, each new user U_i needs to generate his/her chosen random nonce x_i, choose a private password pw_i and select an identity ID_i. Then the user U_i sends the registration request message $\langle ID_i, x_i, pw_i \rangle$ to the server S via a secure channel.

5.3.2. Authenticated key exchange phase

Our authenticated key exchange phase consists of the following steps:

Step 1. $U_i \rightarrow S : m_1 = \{g^{x_i} M^{pw_i}\}$

Step 1.1. Each user U_i chooses a random nonce x_i.

Step 1.2. U_i computes g^{x_i} and $g^{x_i} M^{pw_i}$, using the generator g and public key M of the user U_i.

Step 1.3. U_i then sends the message $\langle m_1 \rangle$, where $m_1 = \{g^{x_i} M^{pw_i}\}$, to the trusted integrated EPR information system server S via a public channel.

Step 2. $S \rightarrow U_i : m_2 = \{g^{y_i} N^{pw_i}, E_{ek_i}[S_n, K_{i-1}, K_i']\}$

Step 2.1. S chooses a random nonce y_i.

Step 2.2. S computes $g^{y_i}, g^{y_i} N^{pw_i}, g^{x_i} = \frac{g^{x_i} M^{pw_i}}{M^{pw_i}}, K_{i-1} \equiv (g^{x_{i-1}})^{y_{i-1}^2} \pmod p$, and $K_i' \equiv (g^{x_{i+1}})^{y_i^2} \pmod p$, using the password pw_i of the user U_i, which is already sent securely to the server S by the user U_i during the registration phase, and N the public key of the server S.

Step 2.3. S then computes encryption key $ek_i \equiv (g^{x_i})^{y_i} \pmod p$, for $i = 1, 2, \ldots, n$. S encrypts the information (S_n, K_{i-1}, K_i') using the computed encryption key ek_i.

Step 2.4. Finally, S sends the message $\langle m_2 \rangle$, where $m_2 = \{g^{y_i} N^{pw_i}, E_{ek_i}[S_n, K_{i-1}, K_i']\}$, to the user U_i via a public channel.

Step 3. $U_i \rightarrow^* : m_3 = \{X_i\}$

Step 3.1. U_i computes the encryption key $ek_i = \left(\frac{g^{y_i} N^{pw_i}}{N^{pw_i}}\right)^{x_i} = g^{x_i y_i} \pmod p$, and obtains K_{i-1} and K_i' by decrypting $E_{ek_i}[S_n, K_{i-1}, K_i']$ with the computed key ek_i.

Step 3.2. If U_i successfully verifies $E_{ek_i}[S_n, K_{i-1}, K_i']$, he/she then computes $Z_i = (K_{i-1})^{x_i} \equiv g^{x_{i-1} x_i y_{i-1}^2} \pmod p$, $Z_{i+1} = (K_i')^{x_i} \equiv g^{x_i x_{i+1} y_i^2} \pmod p$, and $X_i = \frac{Z_{i+1}}{Z_i} = \frac{g^{x_i x_{i+1} y_i^2}}{g^{x_{i-1} x_i y_{i-1}^2}} \pmod p$.

Step 3.3. Finally, U_i broadcasts the message $\langle m_3 \rangle$, where $m_3 = \{X_i\}$.

Step 4. $U_i \rightarrow^* : m_4 = \{Auth_{i1}, Auth_{i2}\}$

Step 4.1. After receiving the message $\langle m_3 \rangle$ in Step 3, U_i computes the secret value sk_i as

$$sk_i = Z_i^n \times X_i^{n-1} \times X_{i+1}^{n-2} \times \cdots \times X_{i-2}^1 = g^{x_1 y_1^2 x_2 + x_2 y_2^2 x_3 + \cdots + x_n y_n^2 x_1} \pmod p.$$

Step 4.2. U_i computes the key conformations $(Auth_{i1}, Auth_{i2})$, where $Auth_{i1} = H(S_n, sk_i, U_i)$ and $Auth_{i2} = H(S_n, K_i')$.

Step 4.3. U_i broadcasts the message $\langle m_4 \rangle$, where $m_4 = \{Auth_{i1}, Auth_{i2}\}$.

Step 4.4. Finally, the user U_i authenticates another user U_j in a group S_n by verifying $Auth_{j1}$, for $i \neq j$, and also computes the common session key SK as $SK = H(S_n, sk_i)$. At the same time, the server S authenticates each user U_i by verifying $Auth_{i2}$.

Table 3 Summary of the user registration and authenticated key exchange phases of our scheme.

User U_i	Server S
Registration phase	
Generates random nonce x_i, selects identity ID_i and password pw_i.	
$\langle ID_i, x_i, pw_i \rangle \xrightarrow{}$	
(via a secure channel)	
Authenticated key exchange phase	
Computes $m_1 = g^{x_i} M^{pw_i}$.	
$\langle m_1 \rangle \xrightarrow{}$	
	Chooses a random nonce y_i, computes $g^{y_i} N^{pw_i}$, $g^{x_i} = \frac{g^{x_i} M^{pw_i}}{M^{pw_i}}$, $K_{i-1} \equiv (g^{x_{i-1}})^{y_{i-1}^2} \pmod p$, and $K_i' \equiv (g^{x_{i+1}})^{y_i^2} \pmod p$. Computes key $ek_i \equiv (g^{x_i})^{y_i} \pmod p$, for $i = 1, 2, \ldots, n$, and encrypts (S_n, K_{i-1}, K_i') using ek_i.
	$\langle m_2 = \{g^{y_i} N^{pw_i}, E_{ek_i}[S_n, K_{i-1}, K_i']\} \rangle \xleftarrow{}$
Computes key $ek_i = \left(\frac{g^{y_i} N^{pw_i}}{N^{pw_i}}\right)^{x_i} = g^{x_i y_i} \pmod p$, retrieves $[S_n, K_{i-1}, K_i'] = D_{ek_i}[E_{ek_i}[S_n, K_{i-1}, K_i']]$. Verifies $E_{ek_i}[S_n, K_{i-1}, K_i']$. If it is successful, computes $Z_i = (K_{i-1})^{x_i} \equiv g^{x_{i-1} x_i y_{i-1}^2} \pmod p$, $Z_{i+1} = (K_i')^{x_i} \equiv g^{x_i x_{i+1} y_i^2} \pmod p$, and $X_i = \frac{Z_{i+1}}{Z_i} = \frac{g^{x_i x_{i+1} y_i^2}}{g^{x_{i-1} x_i y_{i-1}^2}} \pmod p$.	
Broadcasts the message $\langle m_3 = \{X_i\} \rangle$	
Computes $sk_i = Z_i^n \times X_i^{n-1} \times \cdots \times X_{i-2}^1 = g^{x_1 y_1^2 x_2 + x_2 y_2^2 x_3 + \cdots + x_n y_n^2 x_1} \pmod p$.	
Computes $Auth_{i1} = H(S_n, sk_i, U_i)$ and $Auth_{i2} = H(S_n, K_i')$.	
Broadcasts the message $\langle m_4 = \{Auth_{i1}, Auth_{i2}\} \rangle$.	
Verifies $Auth_{j1}$, for $i \neq j$ for each user U_j.	
	Verifies $Auth_{i2}$ for each user U_i.
Computes common session key $SK = H(S_n, sk_i)$.	

Note that by verifying $Auth_{i1}$, the mutual authentication among n users in a group S_n is achieved. On the other hand, by verifying $Auth_{i2}$, the mutual authentication between the server S and n users in the group, S_n is also achieved.

5.3.3. Password change phase

If a legitimate user U_i wants to change his/her password pw_i, he/she needs to send his/her identity ID_i, the old password pw_i and the new password pw_i' to the integrated EPR information system S via a secure channel. After receiving the password change request, the server S verifies the pair (ID_i, pw_i). If it is a valid pair, the server S then replaces the old password pw_i with the new password pw_i' in its database.

The summary of our scheme is given in Table 3.

6. Analysis of our proposed scheme

In this section, we first show that all users in a group S_n have the same secret key. After that through the informal and formal security analysis, we show that our scheme is secure against different attacks.

6.1. Correctness of the protocol

The correctness proof of our scheme is given in Theorem 1.

Theorem 1. *In our improved scheme, all users U_i $(i = 1, 2, \ldots, n)$ in a group S_n have the same secret session key SK.*

Proof. Let U_i be a user in a group S_n consisting of n members. The user U_i in a group S_n computes the secret value sk_i as

$$\begin{aligned} sk_i &= Z_i^n \times X_i^{n-1} \times X_{i+1}^{n-2} \times \cdots \times X_{i-2}^1 \\ &= Z_i^n \times (Z_{i+1}/Z_i)^{n-1} \times (Z_{i+2}/Z_{i+1})^{n-2} \times \cdots \times (Z_{i-1}/Z_{i-2})^1 \\ &= \prod_{i=1}^{n} Z_i \\ &= g^{x_1 y_1^2 x_2 + x_2 y_2^2 x_3 + \cdots + x_n y_n^2 x_1} \pmod p. \end{aligned}$$

As a result, all users U_i $(i = 1, 2, \ldots, n)$ in the group S_n have the same secret session key SK as $SK = H(S_n, sk_i)$. □

6.2. Informal security analysis

In this section, we show that our scheme is secure against various known attacks. For security analysis, we use the threat model described in Section 5.2.

6.2.1. Session key security

In our scheme, no adversary can compute $Z_i(= g^{x_{i-1}x_iy_{i-1}^2} \pmod p)$ even if he/she has the knowledge of $g^{x_{i-1}}, g^{x_i}$ and $g^{y_{i-1}^2}$. This problem is computationally difficult due to difficulty of solving the group Diffie–Hellman problem (Bresson et al., 2003). Moreover, the secret value sk_i depends on the one-time random secrets x_i and y_i $(i = 1, 2, \ldots, n)$. Thus, computing the secret session key $SK = H(S_n, sk_i)$ without computing Z_i is a computationally infeasible for the adversary. Therefore, our scheme provides the session key security.

6.2.2. Mutual authentication

As in Lee et al.'s scheme (Lee et al., 2013), each legal user U_i can decrypt the information in message $\langle m_2 \rangle$ using its own password pw_i, and then compute the one-time encryption key ek_i. Additionally, each user U_i can authenticate the server S by verifying the ciphertext $E_{ek_i}[S_n, K_{i-1}, K_i']$, whereas the server S can also authenticate each user U_i by verifying $Auth_{i2}$. Furthermore, each user U_i can authenticate the other users U_j's $(i \neq j)$ by verifying $Auth_{j1}$ in a group S_n. Our scheme then achieves the mutual authentication between the users and the server, and also among all the users in a group S_n.

6.2.3. Perfect forward security

By the forward security, we mean that when a node (user) leaves the network, it must not read any future messages after its departure. Forward secrecy thus ensures that the subsequent shared session keys cannot be derived even if an adversary knows the contiguous subset of old session keys. In our scheme, the session key SK is the secret value $sk_i = g^{x_1y_1^2x_2 + x_2y_2^2x_3 + \cdots + x_ny_n^2x_1} \pmod p$, which depends on only the one-time random secrets x_i and y_i's $(i = 1, 2, \ldots, n)$. Since the random secrets are not dependent on the private password pw_i of a user U_i, no adversary can compute the previous session keys even if he/she knows private password pw_i of that user U_i. Thus, our proposed scheme provides the perfect forward security to the established session key SK.

6.2.4. Off-line password guessing attack

In the following, we explain how our improved scheme has the ability to resist the weaknesses of Lee et al.'s SGPAKE scheme. From the received message $\langle m_2 \rangle$ in Step 2 during our authenticated key exchange phase, a user U_i in a group S_n can compute the encryption key $ek_i = g^{x_iy_i} \pmod p$, and obtain K_{i-1}, and K_i' by decrypting $E_{ek_i}[S_n, K_{i-1}, K_i']$ with the computed encryption key ek_i, where $K_{i-1} \equiv (g^{x_{i-1}})^{y_{i-1}^2} \pmod p$ and $K_i' \equiv (g^{x_{i+1}})^{y_i^2} \pmod p$. Since x_{i-1} (chosen by the user) and y_{i-1} (chosen by the server) are random nonces corresponding to the user U_{i-1}, the user U_i cannot compute $g^{x_{i-1}}$ and $g^{y_{i-1}}$ using the derived K_{i-1} and K_i', due to difficulty of solving discrete logarithm problem. The user U_i needs to guess both private password, say pw_{i-1}' and one-time random secret, say x_{i-1}' of the user U_{i-1} such that the condition $g^{x_{i-1}'} M^{pw_{i-1}'} \pmod p = g^{x_{i-1}} M^{pw_{i-1}} \pmod p$ holds. Then, the guessed pair (pw_{i-1}', x_{i-1}') may probably be the original pair. However, as pointed out in Das and Goswami (2013), the probability of guessing a correct password pw_{i-1}' of composed n characters is $\approx \frac{1}{2^{6n}}$ and the probability of guessing a correct random nonce x_{i-1} of 1024-bit is $\approx \frac{1}{2^{1024}}$. Moreover, to guess a correct pw_{i-1}', the attacker has to guess the correct x_{i-1}', which is of 1024-bit. Thus, the probability of guessing the probably correct pair (pw_{i-1}', x_{i-1}') is $\approx \frac{1}{2^{6n+1024}}$. If $n = 10$, the success probability is approximately $\frac{1}{2^{60+1024}}$, which is negligible. The user U_i can not compute $M^{pw_{i-1}}$ from message $\langle m_1 = \{g^{x_{i-1}} M^{pw_{i-1}}\} \rangle$ and $N^{pw_{i-1}}$ from $g^{y_{i-1}} N^{pw_{i-1}}$ without knowing $g^{x_{i-1}}$ and $g^{y_{i-1}}$, respectively. Therefore, the user U_i has no way to guess the password correctly of other users in a group S_n with the available public parameters, and hence, our scheme resists the off-line password-guessing attacks.

6.2.5. Undetectable on-line password guessing attack

Suppose an adversary, distinguished as the user U_i, guesses a password, say pw_i' and communicates with the server S. But in Step 4 of our authenticated key exchange phase, to compute the authentication parameters $Auth_{i1}(= H(S_n, sk_i, U_i))$ and $Auth_{i2}(= H(S_n, K_i'))$, the adversary needs to retrieve the original K_{i-1} and K_i' from the ciphertext $E_{ek_i}[S_n, K_{i-1}, K_i']$. Computing K_{i-1} and K_i' without knowledge of the encryption key $ek_i(= g^{x_iy_i} \pmod p)$ and computing Z_i (used in computing sk_i) without knowing the correct pair (pw_i, x_i) are computationally infeasible tasks to the attacker. Thus, a failed password guessing will be detected by other users as well as the server. On other hand, suppose an adversary, distinguished as the server S, guesses a password, say pw_i' and communicates with the users U_i's in a group S_n. After receiving the message $\langle m_1 \rangle$ from the user U_i, the adversary needs to compute $g^{x_i} = \frac{g^{x_i} M^{pw_i'}}{M^{pw_i'}}$ using a guessed password pw_i'. Then, the adversary needs to compute K_{i-1} and $K_i'(= (g^{x_{i+1}})^{y_i^2} \pmod p)$, $K_{i-1}(= (g^{x_{i-1}})^{y_{i-1}^2} \pmod p)$ and the encryption key $ek_i(= g^{x_iy_i} \pmod p)$. Moreover, the adversary has to compute the ciphertext $E_{ek_i}[S_n, K_{i-1}, K_i']$ and send the message, say $m_2'(= \{g^{x_i} M^{pw_i'}, E_{ek_i}[S_n, K_{i-1}, K_i']\})$ to the user U_i. Since the user U_i can verify $\langle m_2' \rangle$ in Step 3 of our authenticated key exchange phase, a failed password guessing will be detected by the user U_i. As a result, our scheme prevents the undetectable on-line password guessing attack.

6.2.6. Data privacy and users' privacy

In our improved scheme, computing a session key is computationally infeasible task as described in Section 6.2.1. So, no adversary can decrypt the transmitted data without the common session key. Moreover, our scheme provides private password to each user in a group and also prevents the password guessing attacks. Therefore, our scheme provides data privacy as well as users' privacy, whereas Lee et al.'s scheme does not provide the users' privacy as their scheme is vulnerable to off-line password-guessing attacks.

6.2.7. Known-key security

Each run of our authenticated key exchange phase between a specific user U_i and the server S produces a unique session

secret key. This property ensures that when the protocol has known key security, the knowledge of previous session keys does not allow an adversary to compromise other previous session keys or future session keys (Ammayappan et al., 2011). Since the session key is different for different sessions and they are independent among each protocol execution, our improved scheme also exhibits the known-key security property.

6.3. Formal security analysis

We follow the formal security proof of our improved scheme as in Das (2013), Das et al. (2012) and Odelu et al. (2014). For this purpose, we first formally define the discrete logarithm problem (DLP). We present the formal security proof of our scheme only for users' privacy and perfect forward security in Theorem 2, whereas other security analyses are already provided in Section 6.2. For the formal security analysis, we follow the method using the random oracle model as used in Chatterjee et al. (2014), Das et al. (2013), Islam and Biswas (2013) and Islam and Biswas, 2014.

Definition 1. (Formal definition of discrete logarithm problem (Das, 2013)) Let G be a cyclic group of order q, g a generator of G, and A_1 an algorithm that return an integer in Z_q, where $Z_q = \{0, 1, \ldots, q-1\}$. Let $a \in_R T$ denote that the element a is chosen randomly from the set T. Consider the following experiment, $EXP1_{G,g}^{DLP}(A_1)$ in Algorithm 1.

Algorithm 1.

$EXP1_{G,g}^{DLP}(A_1)$

1: $x \in_R Z_q$
2: $X \leftarrow g^x \pmod q$
3: $x' = A_1(X)$
4: **if** $g^{x'} = X \pmod q$ **then**
5: **return** 1 (TRUE)
6: **else**
7: **return** 0 (FALSE)
8: **end if**

The DLP advantage of A_1 is defined by $Adv_{G,g}^{DLP}(A_1) = Pr[EXP1_{G,g}^{DLP}(A_1) = 1]$, where $Pr[E]$ denotes the probability of an event E in a random experiment. The discrete logarithm problem (DLP) is called a hard problem (computationally infeasible problem) in G if the DLP-advantage of any adversary of reasonable resources is small. Here the resources are measured in terms of the time complexity of the adversary including its code size as usual. In other words, we call the DLP as a hard problem, if $Adv_{G,g}^{DLP}(A_1) \leqslant \epsilon$, for any sufficiently small $\epsilon > 0$.

Theorem 2. *Under the assumption of the discrete logarithm problem, our improved scheme is provably secure against an adversary for protecting users' privacy and perfect forward security.*

Proof. In this proof, we need to construct an adversary $\mathcal{A}$ from a dynamic group S_n consisting of n users, who can obtain the private password of the other members in that group S_n using the available information including his/her own private password. In order to construct such an adversary $\mathcal{A}$, we consider the following random oracle:

- *Reveal*: This oracle unconditionally outputs the value $x \in Z_q$ from the given public value $g^x \pmod q$, where g is the generator in the cyclic group G of order q.

Assume that the adversary $\mathcal{A}$ is a user U_i in the dynamic group S_n. The adversary $\mathcal{A}$ needs to run the experimental algorithm $EXP2_{IP,\mathcal{A}}^{DLP}$ for our improved protocol, say IP, given in Algorithm 2.

Algorithm 2.

$EXP2_{IP,A}^{DLP}$

1: U_i (being an adversary $\mathcal{A}$) eavesdrops the message $m_2 = \{g^{y_i} N^{pw_i}, E_{ek_i}[S_n, K_{i-1}, K_i']\}$ sent from the server S.
2: U_i computes $g^{y_i} = \frac{g^{y_i} N^{pw_i}}{N^{pw_i}}$ using his/her private password pw_i and public N.
3: U_i obtains K_{i-1} and K_i' by decrypting $E_{ek_i}[S_n, K_{i-1}, K_i']$ using the encryption key ek_i, where $ek_i = (g^{y_i})^{x_i} \pmod p$.
4: Call *Reveal* oracle on input g^{y_i}. Let $y_i' \leftarrow Reveal(g^{y_i})$.
5: U_i computes $g^{x_{i+1}} = (K_i')^{(y_i')^{-2}} \pmod p$ and then computes $M^{pw_{i+1}} = \frac{g^{x_{i+1}} M^{pw_{i+1}}}{g^{x_{i+1}}}$.
6: Call *Reveal* oracle on input $M^{pw_{i+1}}$. Let $pw_{i+1}' \leftarrow Reveal(M^{pw_{i+1}})$.
7: **if** $M^{pw_{i+1}'} = M^{pw_{i+1}} \pmod p$ **then**
8: **return** 1 (TRUE)
9: **else**
10: **return** 0 (FALSE)
11: **end if**

We now define the success for $EXP2_{IP,\mathcal{A}}^{DLP}$ as $Succ_{IP,\mathcal{A}}^{DLP} = |Pr[EXP2_{IP,\mathcal{A}}^{DLP} = 1] - 1|$ and the advantage function for our improved protocol, IP due to this experiment as $Adv_{IP}^{DLP}(t, q_R) = max_{\mathcal{A}}\{Succ_{IP,\mathcal{A}}^{DLP}\}$, where the maximum is considered over all $\mathcal{A}$ with execution time t and q_R is the number of queries made to the *Reveal* oracle. Consider the experiment $EXP2_{IP,\mathcal{A}}^{DLP}$ for the adversary $\mathcal{A}$ for our improved scheme, IP. If $\mathcal{A}$ has the ability to solve DLP, the adversary wins the game, and thus, the adversary obviously can easily compute the nonce y_i from the public message $g^{y_i} N^{pw_i}$ using his/her private password pw_i. Using the derived nonce y_i and K_i', he/she can compute the private password pw_{i+1} of the user U_{i+1}. In this case, the adversary can derive the private passwords of all users in the dynamic group S_n. However, from Definition 1, DLP is a hard problem, that is, $Adv_{G,g}^{DLP}(A_1) \leqslant \epsilon$, for any sufficiently small $\epsilon > 0$. Hence, $Adv_{IP}^{DLP}(t, q_R) \leqslant \epsilon$, since $Adv_{IP}^{DLP}(t, q_R)$ depends on $Adv_{G,g}^{DLP}(A_1)$. As a result, there is no feasible way for the adversary to obtain the private password of any other user in the group S_n. Therefore, our proposed protocol provides the users' privacy.

A compromised password does not yield any previous session keys SK, because the session key $SK = H(S_n, sk_i)$, where $sk_i = g^{x_1 y_1^2 x_2 + x_2 y_2^2 x_3 + \cdots + x_n y_n^2 x_1} \pmod p$, depends on the temporarily chosen random nonces $x_1, x_2, \ldots, x_n$ and

$y_1, y_2, \ldots, y_n$, and it is independent of protocol executions. As a result, our improved scheme preserves the perfect security property. □

7. Simulation for formal security verification using AVISPA tool

In this section, we examine our scheme through simulation for the formal security verification using the widely-accepted AVISPA tool (Das, 2013; Das et al., 2013), and show that our scheme is secure against active attacks, such as replay and man-in-the-middle attacks.

AVISPA (Automated Validation of Internet Security Protocols and Applications) stands for a push-button tool for the automated validation of Internet security-sensitive protocols and applications (AVISPA, 2013). AVISPA consists of four different back-ends that implement a variety of state-of-the-art automatic analysis techniques, which are called the On-the-fly Model-Checker (OFMC), Constraint Logic based Attack Searcher (CL-AtSe), SAT-based Model-Checker (SATMC), and Tree Automata based on Automatic Approximations for the Analysis of Security Protocols (TA4SP). The protocols to be analyzed under the AVISPA tool require to specify them in a high-level language, called HLPSL (High Level Protocols Specification Language), which is a role-oriented language. The specification written in HLPSL is first translated into a low-level specification by a translator, called HLPSL2IF. This translator generates a specification in an intermediate format, called the Intermediate Format (IF). After that the output format (OF) of AVISPA is generated using one of the four back-ends: OFMC, CL-AtSe, STAMC and TA4SP. The analysis of the OF is made as follows. The first printed section called SUMMARY, indicates whether the protocol is safe, unsafe, or whether the analysis is inconclusive. DETAILS is the second section, which explains under what condition the protocol is declared safe, or what conditions have been used for finding an attack, or finally why the analysis was inconclusive. Other remaining sections, called PROTOCOL, GOAL and BACKEND, represent the name of the protocol, the goal of the analysis and the name of the back-end used, respectively. Finally, at the end of the analysis, after some possible comments and the statistics, the trace of the attack (if any) is also printed in the usual Alice-Bob format. One can find more details on HLPSL in Advanced Encryption Standard (2010) and AVISPA (2013).

Some basic types available in HLPSL are (Advanced Encryption Standard, 2010; AVISPA, 2013):

- *agent:* Values of type *agent* represent principal names. The intruder is always assumed to have the special identifier *i*.
- *public_key:* These values represent agents' public keys in a public-key cryptosystem. For example, given a public (respectively private) key *pk*, its inverse private (respectively public) key is obtained by *inv_pk*.
- *symmetric_key:* Variables of this type represent keys for a symmetric-key cryptosystem.
- *text:* In HLPSL, *text* values are often used as nonces. These values can be used for messages. If *Na* is of type *text (fresh)*, then *Na*′ will be a fresh value which the intruder cannot guess.
- *nat:* The *nat* type represents the natural numbers in non-message contexts.
- *const:* This type represents constants.
- *hash_func:* The base type *hash_func* represents cryptographic hash functions. The base type function also represents functions on the space of messages. It is assumed that the intruder cannot invert hash functions (in essence, that they are one-way).
- *bool:* Boolean values are useful for modeling, for instance, binary flags.

The space of legal messages is defined as the closure of the basic types. For a given message M and encryption key K, we denote $\{M\}\_K$ as the symmetric/public-key encryption using the key K. For concatenations, HLPSL uses the associative "." operator. The "*played_by A*" declaration indicates that the agent named in variable A plays in a particular role. A knowledge declaration (generally in the top-level *Environment* role) is used to specify the intruder's initial knowledge. The immediate reaction transitions have the form $X = | > Y$, which relate an event X and an action Y. If a variable V remains permanently secret, it is expressed by the goal *secrecy_of V*. If V is ever obtained or derived by the intruder, a security violation will result. The intruder, always denoted by (i), will have the ability to intercept, analyze, and/or modify messages transmitted over the insecure channel. $witness(A, B, id, E)$ declares for a (weak) authentication property of A by B on E, declares that agent A is witness for the information E; this goal will be identified by the constant *id* in the goal section (AVISPA, 2013). This expresses that the agent named in variable B has freshly generated the value E for the agent named in variable A. The *id* term is a new constant that identifies the message term upon which the goal should authenticate. $request(B, A, id, E)$ indicates for a strong authentication property of A by B on E, declares that agent B requests a check of the value E; this goal will be identified by the constant *id* in the goal section (AVISPA, 2013). This formalizes A's acceptance of the value E as having generated for him/her by the agent named in B.

7.1. Specifying our scheme

The specification in HLPSL language for the role of the user U_i in a group S_n is shown in Fig. 1. At first, during the registration phase of our scheme, a user U_i sends the registration message $\langle ID_i, x_i, pw_i \rangle$ to the server S via a secure channel using the $Snd()$ operation. The channel declaration $channel(dy)$ means that the channel is insecure, which is based the Dolev–Yao threat model (as used in our threat model in Section 5.2) (Dolev and Yao, 1983). Note that secret(Xi, PWi, subs1, Ui) declares that both x_i and pw_i are kept secret to U_i only using the protocol id, subs1. During the authenticated key exchange phase, U_i sends the message $\langle m_1 = \{g^{x_i} M^{pw_i}\} \rangle$ via a public channel. After receiving the message $\langle m_2 = \{g^{y_i} N^{pw_i}, E_{ek_i}[S_n, K_{i-1}, K_i']\} \rangle$ from the server S by the $Rcv()$ operation, U_i broadcasts the messages $\langle m_3 = \{X_i\} \rangle$ and $\langle m_4 = \{Auth_{i1}, Auth_{i2}\} \rangle$. witness(Ui, S, alice_bob_xi, Xi) indicates that U_i has freshly generated the value x_i for the server S. By request(S, Ui, bob_alice_yi, Yi), U_i accepts of the random nonce y_i generated for U_i by the server S. In a similar way, we have also implemented the specification in HLPSL language for the roles of the server S and another user U_j in a group S_n in Figs. 2 and 3, respectively.

```
role useri (Ui, Uj, S   : agent,
            SKus : symmetric_key,
            % H is hash function
            H : hash_func,
            Snd, Rcv: channel(dy))
played_by Ui
def=
 local State  : nat,
       % F is the other function (such as
       % multiplication, squaring, etc.)
       F : hash_func,
       P, M, N, G : text,
       IDi, Sn, PWi, Xi, Yi, EKi: text,
       SKi, K1, K2, Xi1, Xi2, Yi1: text
 const alice_bob_xi,  bob_alice_yi,
       subs1, subs2, subs3, subs4 : protocol_id
init  State := 0
transition
% User registration phase
1. State = 0 /\ Rcv(start) =|>
   State' := 1 /\ Xi' := new()
% Send the registration request message
           /\ Snd({IDi.Xi'.PWi}_SKus)
           /\ secret({Xi', PWi}, subs1, Ui)
           /\ secret({SKi}, subs3, {Ui,Uj,S})
% Authenticated key exchange phase
% Send the message <m1> to the server S via a
% public channel
2. State = 1 /\ Snd(F(exp(G,Xi').exp(M,PWi)))
% Receive the message <m2> from server S via
% a public channel
          /\ Rcv(F(exp(G,Yi').exp(N,PWi)).
             {Sn.exp(G,F(Xi1.Yi1)).
             exp(G,F(Xi2,Yi))}_(exp(exp(G,Xi'),Yi'))) =|>
% Send the message <m3>
   State' := 2 % Ui has freshly generated the value Xi' for S
           /\ witness(Ui, S, alice_bob_xi, Xi')
           /\ Snd(F(exp(G,F(Xi'.Xi2.Yi')).
                exp(G, F(Xi1.Xi'.Yi1))))
            /\ secret({Yi'}, subs2, S)
% Send the message <m4>
           /\ K2' := exp(G,F(Xi2,Yi'))
           /\ Snd(H(Sn.SKi.Ui).H(Sn.K2'))
 % Ui's acceptance of the value Yi' generated for Ui by S
           /\ request(S, Ui, bob_alice_yi, Yi')
end role
```

Figure 1 Role specification in HLPSL for a user U_i in a group S_n of our scheme.

```
role  server (Ui, Uj, S   : agent,
           SKus : symmetric_key,
           % H is hash function
           H : hash_func,
           Snd, Rcv: channel(dy))
played_by S
def=
 local State  : nat,
       % F is the other function (such as
       % multiplication, squaring, etc.)
       F : hash_func,
       P, M, N, G : text,
       IDi, IDj, Sn, PWi, PWj, Xi, Xj, Yi, EKi: text,
       SKi, K1, K2, Xi1, Xi2, Yi1: text
 const alice_bob_xj,  bob_alice_yi,
       subs1, subs2, subs3, subs4 : protocol_id
init  State := 0
 transition
% User registration phase
% Receive the registration request messages from Ui and Uj
1. State  = 0 /\ Rcv({IDi.Xi'.PWi}_SKus)  =|>
   State' := 1 /\ secret({Xi', PWi}, subs1, Ui)
          /\ secret({SKi}, subs3, {Ui,Uj,S})
2. State = 1 /\ Rcv({IDj.Xj'.PWj}_SKus) =|>
   State' := 2 /\ secret({Xj', PWj}, subs4, Uj)
% Authenticated key exchange phase
% Receive the message <m1> to Ui via a
% public channel
2. State = 2 /\ Rcv(F(exp(G,Xi').exp(M,PWi))) =|>
% S has freshly generated the value Yi' for Ui
   State' := 3
3. State = 3  /\ Rcv(F(exp(G,Xj').exp(M,PWj))) =|>
% Send the message <m2> to Ui via
% a public channel
   State' := 4 /\ Yi' := new()
            /\ Snd(F(exp(G,Yi').exp(N,PWi)).
            {Sn.exp(G,F(Xi1.Yi1)).
            exp(G,F(Xi2,Yi'))}_(exp(exp(G,Xi),Yi')))
% S has freshly generated the value Yi' for Ui
          /\ witness(S, Ui, bob_alice_yi, Yi')
% Receive the message <m3> from Ui
4. State = 4 /\ Rcv(F(exp(G,F(Xi'.Xi2.Yi')).
               exp(G, F(Xi1.Xi'.Yi1)))) =|>
   State' := 5 /\ secret({Yi'}, subs2, S)
% Receive the message <m4>
5. State = 5 /\ Rcv(H(Sn.SKi.Ui).H(Sn.exp(G,F(Xi2,Yi')))) =|>
 % S's acceptance of the value Xi' generated for S by Ui
  State' := 6 /\ request(Ui, S, alice_bob_xi, Xi)
 % S's acceptance of the value Xj' generated for S by Uj
          /\ request(Uj, S, alice_bob_xj, Xj)
end role
```

Figure 2 Role specification in HLPSL for the server S of our scheme.

We have then specified the roles for the session, and the goal and environment of our scheme in Figs. 3 and 4. In the session segment, all the basic roles: useri, userj and server are instanced with concrete arguments. The top-level role, called the environment, is always defined in the specification of HLPSL language, which contains the global constants and a composition of one or more sessions, where the intruder may play some roles as legitimate users. The intruder also participates in the execution of protocol as a concrete session during the simulation. Goals are given in their own sections, which generally come at the end of a HLPSL specification. Goal is defined with the keyword *goal* and ends with *end goal*. Between the two, multiple security goals may be listed in HLPSL.

The following four secrecy goals and three authentications are verified in our scheme for formal security verification:

```
role userj (Ui, Uj, S   : agent,
            SKus : symmetric_key,
            % H is hash function
            H : hash_func,
            Snd, Rcv: channel(dy))
played_by Uj
def=
 local State  : nat,
       % F is the other function (such as
       % multiplication, squaring, etc.)
       F : hash_func,
       P, M, N, G : text,
       IDj, Sn, PWj, Xi, Xj, Yi, EKi: text,
       SKi, K1, K2, Xi1, Xi2, Yi1: text
 const alice_bob_xj,  bob_alice_yi,
       subs1, subs2, subs3, subs4 : protocol_id
init  State := 0
transition
% User registration phase
1. State = 0 /\ Rcv(start) =|>
   State' := 1 /\ Xj' := new()
% Send the registration request message
           /\ Snd({IDj.Xj'.PWj}_SKus)
           /\ secret({Xj', PWj}, subs4, Uj)
           /\ secret({SKi}, subs3, {Ui,Uj,S})
% Authenticated key exchange phase
% Send the message <m1> to the server S via a
% public channel
2. State = 1 /\ Snd(F(exp(G,Xj').exp(M,PWj)))
% Receive the message <m3>
            /\ Rcv(F(exp(G,F(Xi'.Xi2.Yi')).
                 exp(G, F(Xi1.Xi'.Yi1)))) =|>
% Receive the message <m4>
State' := 2  % Uj has freshly generated the value Xj' for S
           /\ witness(Uj, S, alice_bob_xj, Xj')
3. State = 2 /\ Rcv(H(Sn.SKi.Ui).H(Sn.exp(G,F(Xi2,Yi')))) =|>
 % Uj's acceptance of the value Yi' generated for Uj by S
State' := 3  /\ request(S, Uj, bob_alice_yi, Yi)
end role
```

Figure 3 Role specification in HLPSL for another user U_j in a group S_n of our scheme.

- secrecy_of subs1: It represents that the generated random nonce x_i and the password pw_i are kept secret to the user U_i only.
- secrecy_of subs2: It represents that the generated random nonce y_i is kept secret to the server S only.
- secrecy_of subs3: It represents that the secret value sk_i is kept secret to the users U_i, U_j and the server S.
- secrecy_of subs4: It represents that the generated random nonce x_j and the password pw_j are kept secret to another user U_j in a group only.
- authentication_on alice_bob_xi: U_i generates a random nonce x_i, where x_i is only known to U_i. When the server S receives x_i from the messages from U_i, S authenticates U_i.
- authentication_on alice_bob_xj: U_j generates a random nonce x_j, where x_j is only known to U_j. When the server S receives x_j from the messages from U_j, S authenticates U_j.
- authentication_on bob_alice_yi: S_j generates a random nonce y_i, where y_i is only known to S. When the user U_i receives y_i from the messages from S, U_i authenticates S.

```
role session(Ui, Uj, S: agent,
             SKus : symmetric_key,
             H : hash_func)
def=
  local  S1, S2, S3, R1, R2, R3: channel (dy)
composition
          useri(Ui, Uj, S, SKus, H, S1, R1)
       /\  userj(Ui, Uj, S, SKus, H, S2, R2)
       /\  server(Ui, Uj, S, SKus, H, S3, R3)
end role


role environment()
def=
  const ui, uj, s: agent,
        skus : symmetric_key,
        h   : hash_func,
        alice_bob_xi, alice_bob_xj,
        bob_alice_yi, subs1, subs2,
        subs3, subs4 : protocol_id
  intruder_knowledge = {ui, uj, s, h}
  composition
   session(ui, uj, s, skus, h)
/\ session(ui, uj, s, skus, h)
       /\ session(ui, uj, s, skus, h)
end role

goal
  secrecy_of subs1
  secrecy_of subs2
  secrecy_of subs3
  secrecy_of subs4
  authentication_on alice_bob_xi
  authentication_on alice_bob_xj
  authentication_on bob_alice_yi
end goal
environment()
```

Figure 4 Role specification in HLPSL for the session and environment of our scheme.

7.2. *Analysis of results*

We have simulated our improved scheme using the AVISPA web tool (AVISPA, 2014) for CL-AtSe back-end. For the replay attack checking, the back-end checks whether the legitimate agents can execute the specified protocol by performing a search of a passive intruder. After that the back-end gives the intruder the knowledge of some normal sessions between the legitimate agents. For the Dolev–Yao model check, the back-end checks whether there is any man-in-the-middle attack possible by the intruder. The simulation results for the formal security verification of our scheme using this back-end are shown in Fig. 5. The summary of the results under this back-end clearly shows that our scheme is safe. As a result, our scheme is secure against the passive attacks and the active attacks, such as the replay and man-in-the-middle attacks.

8. Performance comparison with related schemes

In this section, we compare the performance of our scheme with Lee et al.'s SGPAKE scheme and other related existing

```
SUMMARY
  SAFE

DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
  TYPED_MODEL

PROTOCOL
  /home/avispa/web-interface-computation/
  ./tempdir/workfileGQXn6b.if

GOAL
  As Specified

BACKEND
  CL-AtSe

STATISTICS

  Analysed   : 9 states
  Reachable  : 1 states
  Translation: 0.33 seconds
  Computation: 0.01 seconds
```

Figure 5 The result of the analysis using CL-AtSe backend of our scheme.

schemes (Abdalla et al., 2006; Boyd and Nieto, 2003; Dutta and Barua, 2006; Kim et al., 2004; Lee et al., 2013).

Table 4 shows the performance comparison of our scheme with Lee et al.'s SGPAKE scheme (Lee et al., 2013), Abdalla et al.'s scheme (Abdalla et al., 2006), Dutta and Barua's scheme (Dutta and Barua, 2006), Kim et al.'s scheme (Kim et al., 2004) and Boyd and Nieto's scheme (Boyd and Nieto, 2003). Boyd and Nieto's scheme (Boyd and Nieto, 2003) and Kim et al.'s scheme (Kim et al., 2004) are based on the public key infrastructure (PKI) and they provide higher security. However, they are required to maintain the complex and heavy public key systems, and also the users must hold extra storage for keeping public/private key pairs. Moreover, Boyd and Nieto's scheme (Boyd and Nieto, 2003) lacks forward security, but Kim et al.'s scheme (Kim et al., 2004) protocol can provide the forward security. Abdalla et al.'s scheme (Abdalla et al., 2006), Dutta and Barua's scheme (Dutta and Barua, 2006), Lee et al.'s scheme (Lee et al., 2013) and our proposed improved scheme are not required to maintain the public key system. Each user only needs to remember his/her weak password without any extra equipment for storing long-term secret keys. Lee et al.'s scheme (Lee et al., 2013) requires expensive exponential computations than Dutta and Barua's scheme and Abdalla et al.'s scheme. However, Zhang et al. (2012) showed that Dutta and Barua's scheme (Dutta and Barua, 2006) is insecure. In addition, Dutta and Barua's scheme and Abdalla et al.'s scheme do not provide users' privacy. In Lee et al.'s SGPAKE scheme (Lee et al., 2013), it needs to compute four exponents $g^{x_i}M^{pw_i}$, $K_i = \left(\frac{g^{y_i}N^{pw_i}}{N^{pw_i}}\right)^{x_i} = g^{x_i y_i}$, $Z_i = (K_{i-1})^{x_i}$ and $Z_{i+1} = (K_i')^{x_i}$, whereas the values M^{pw_i} and N^{pw_i} are pre-computed. Instead of computing the parameters $K_i = g^{x_i y_i}$, $K_{i-1} = g^{x_{i-1}y_{i-1}}$ and $K_i' = g^{x_{i+1}y_i}$ in Step 2 of the authentication and key exchange phase in Lee et al.'s SGPAKE scheme, we have computed $ek_i = g^{x_i y_i}$, $K_{i-1} = g^{x_{i-1}y_{i-1}^2}$ and $K_i' = g^{x_{i+1}y_i^2}$. As a result, our improved scheme takes only one extra field exponentiation to compute the encryption key ek_i (at the server side) to enhance the security of Lee et al.'s SGPAKE scheme. As in Abdalla et al.'s scheme, Dutta–Barua's scheme, Kim et al.'s scheme, Boyd–Nieto's scheme and Lee et al.'s SGPAKE scheme, in our scheme we have also omitted the exponents required to compute the secret value $sk_i = Z_i^n \times X_{i+1}^{n-1} \times X_{i+2}^{n-2} \times \cdots \times X_{i+n-1}^1$. In addition, our scheme does not require any public key encryption and decryptions, whereas Boyd–Nieto's scheme requires a total of $2(n-1)$ public key encryption and decryptions, where n is the number of members in a dynamic group S_n. Our scheme, Abdalla et al.'s scheme, Dutta–Barua's scheme and Lee et al.'s SGPAKE scheme do not require any cost for generating and verifying signatures. However, in Kim et al.'s scheme and Boyd–Nieto's scheme the number of signature generation and verification is $2n$ and n, respectively. From this table, it is clear that our scheme is efficient as compared to other schemes. Furthermore, our scheme provides formal security analysis and verification using AVISPA tool. Considering better security as compared to other related schemes, our scheme is much more applicable for practical applications.

Table 4 Comparison of our improved scheme with related schemes.

	Abdalla et al. (2006)	Dutta and Barua (2006)	Kim et al. (2004)	Boyd and Nieto (2003)	Lee et al. (2013)	Ours
User's public key	No	No	Yes	Yes	No	No
Formal security	Yes	Yes	Yes	Yes	No	Yes
User's privacy	A password shared with all users	A password shared with all users	PKI based	PKI based	A private password	A private password
Asymmetric en/decryption	0	0	0	$2(n-1)$ (total)	0	0
Signing/verifying	0	0	$2n$ (total)	n (total)	0	0
Exponentiation	3	3	2	0	4(2[a])	5(2[a])
Symmetric encryption/decryption	3	$n+3$	0	0	1	1
Whether provides forward security	Yes	No	Yes	No	Yes	Yes
Whether provides users' privacy	No	No	Yes	Yes	No	Yes

[a] Two modular exponential computations can be pre-computed and thus they are ignored.

9. Conclusion

In this paper, we have first reviewed Lee et al.'s SGPAKE scheme. We have then shown that their scheme is vulnerable to off-line password-guessing attack and thus, their scheme fails to provide the users' privacy property. To remedy the security weakness found in Lee et al.'s SGPAKE scheme, we have proposed an effective improvement over Lee et al.'s SGPAKE scheme while retaining the original merits of Lee et al.'s SGPAKE scheme. We have provided both informal and formal security analysis of our scheme, and shown that our improved scheme is secure against various known attacks including off-line weak password guessing attack which is found in Lee et al.'s SGPAKE scheme. Therefore, our scheme provides data as well as users' privacy whereas Lee et al.'s scheme does not provide those properties. Moreover, our improved scheme is also efficient as compared to the other related schemes such as Abdalla et al.'s scheme, Dutta–Barua's scheme, Kim et al.'s scheme, Boyd–Nieto's scheme, and Lee et al.'s scheme. In addition, we have simulated our scheme for the formal security analysis using the widely-accepted AVISPA tool and shown that our scheme is secure against active and passive attacks. As a result, our scheme is much suitable for practical scenarios as compared to Lee et al's SGPAKE scheme and other related schemes.

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