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Research Article

An Efficient and Provably-Secure Certificateless Proxy-Signcryption Scheme for Electronic Prescription System

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Electronic prescription is increasingly popular in our society, particularly in technologically advanced countries. Due to strict legal requirements and privacy regulations, authorization and data confidentiality are two important features in electronic prescription system. By combining signature and encryption functions, signcryption is an efficient cryptographic primitive that can be used to provide these two features. While signcryption is a fairly established research area, most signcryption schemes proposed recently have several limitations (e.g., high communication costs, limited bandwidth, and insecurity), and designing secure and practical signcryption schemes remains challenging. In this paper, we propose an improved certificateless proxy signcryption (CLPSC) scheme, based on elliptic curve cryptography (ECC). We also demonstrate that the proposed CLPSC scheme is secure in the random oracle model and evaluate its performance with related schemes. The security and performance evaluations show that the proposed CLPSC scheme can potentially be implemented on resource-constrained low-computing mobile devices in an electronic prescription system.

1. Introduction

Recent advances in cryptographic techniques and consumer and communication technologies have resulted in the migration of services from the brick-and-mortar model to an online model, where transactions are being conducted from mobile devices (e.g., Android and iOS devices and potentially wearable and embedded devices). One such industry application is electronic prescriptions (e-prescriptions) [1, 2], where prescriptions are being sent electronically from a medical practitioner/medical practice to the pharmacist/pharmacy. Payments can also be made online (e.g., using credit cards or bank transfers), and the medications can either be picked up from the pharmacy or delivered to the user's home [3]. Benefits of an e-prescription system extend beyond mere convenience to the users. For example, pharmacists no longer have to 'decipher' the hand-written prescription, which saves time and costs (e.g., having to call the medical practitioner to confirm the actual prescription) and minimizing the chance for errors [4]. Such errors can be fatal. For example, in a study by Brits and Verma [5], it was found that illegible handwriting and other prescription errors on prescriptions resulted in "lorazepam injection 4 mg" being misread as "40 mg (lethal dose) by 20% of [the] healthcare workers."

There are situations where the patient may not be able to collect the medication in person, for example, due to physical injury or medical condition (e.g., severe gout attack resulting in the patient unable to walk and collect prescribed medication such as Colchicine). Thus, the patient has to give another individual (e.g., family member or neighbor) the proxy delegation to collect the medication on his/her behalf. Pharmacists have legal obligations when handling, dispensing, and supplying medications, particularly drugs of dependence. Therefore, it is important to ensure the security and efficiency of generating such a delegation in the e-prescription system.

One such solution is proxy signcryption, as it allows the delegation of signing privileges in computing devices such as mobile devices. The security of such schemes, as well as many other cryptographic schemes (e.g., key agreement and signature schemes), generally relies on the intractability of hard problems such as Diffie-Hellman problem, integer factorization problem, and discrete logarithm problem [6–10]. In recent times, there have been a large number of proxy-signcryption schemes proposed that are based on bilinear pairings [11–13]. However, such schemes often have high computational and communication costs; thus, they are not suited for deployment on mobile devices. Hence, there have been attempts to design pairing-free proxy-signcryption schemes, such as the certificateless proxy-signcryption (CLPSC) schemes of Liu et al. [14] and Qi et al. [15]. The design of such schemes is challenging. For example, Liu et al. [14] proposed a pairing-free CLPSC scheme based on elliptic curve cryptography (ECC), with reduced computational and communication costs. This scheme is, however, vulnerable to public key replacement attack when deployed on resource-constrained devices.

More recently in 2017, Bhatia and Verma [16] proposed an efficient ECC-based pairing-free CLPSC scheme. However, we reveal in this paper that Bhatia and Vermas's scheme also cannot resist the public key replacement attack. Specifically, we demonstrate that it is vulnerable to a public key replacement attack by a Type 1 adversary. Then, we propose an improved protocol to mitigate the security weakness. We also demonstrate the security of the improved protocol in the random oracle model and compare with other related schemes in terms of computation costs and security properties.

In the next section, we present relevant background materials. In Section 3, we reveal the vulnerability in the scheme of Bhatia and Verma. Then, we present the proposed scheme in Section 4 and analyze its security in Section 5. A comparative analysis with existing schemes is presented in Section 6. Finally, we conclude this paper in Section 7.

2. Preliminaries

2.1. Syntax Definition of CLPSC Scheme. In general, the CLPSC scheme comprises three different entities: an original signcrypter (OS), a receiver (R), and a proxy signcrypter (PS). An OS (e.g., a patient) delegates to PS (e.g., a trusted individual such as a family member or neighbor) the authority to signcrypt a message [17, 18]. During proxy signcryption, OS sends his/her signing authority to PS with a delegation warrant, which consists of the identities of the delegator, a message space, and the validity time of the delegation. The warrant requires OS's signature and PS's public key. PS will generate a signcrypted ciphertext with its signature and send a signcrypted ciphertext to R. Upon receiving the signcrypted ciphertext, R (e.g., the pharmacist) unsigncrypts it and checks whether the proxy signature is valid. If it is valid, then PS is authorized to perform tasks such as collect OS' medication; otherwise, PS' request is denied. The CLPSC scheme contains the following polynomial algorithms:

(i) **Setup:** This algorithm invoked by a Key Generation Center (KGC). It takes security parameter k as an input and runs setup algorithm to obtain system parameter ψ and the master key s.

(ii) **Extract-Partial-Private-Key:** KGC takes system parameters ψ, master key s, and a user ID as inputs and outputs the partial private key d_{ID} of the user.

(iii) **Set-Secret:** This algorithm takes security parameter k and system parameters ψ as inputs and outputs the secret value s_{ID}.

(iv) **Set-Private Key:** It inputs system parameters ψ, a user's secret value s_{ID}, and a user's partial private key d_{ID} and outputs the public key $SK_{ID} = (s_{ID}, d_{ID})$.

(v) **Set-Public Key:** It inputs system parameters ψ and a user's secret value x_{ID} and outputs the public key $PK_{ID} = (P_{ID}, K_{ID})$.

(vi) **Gen-Delegation:** It inputs system parameter ψ, a warrant M_W, an ID, and public/private key of the original signer and then outputs a partial proxy key.

(vii) **Verify-Delegation:** It inputs system parameter ψ, a warrant M_W, a partial proxy key, an original signer's ID, and his/her public key, using the protocol to check whether the partial proxy key is from a legitimate user. If yes, then it outputs 1; otherwise, it outputs 0.

(viii) **Gen-Proxy-Key:** It inputs the system parameter ψ, the partial proxy key, and the proxy signer's partial key and outputs a proxy key.

(ix) **Proxy-Signcryption:** It inputs the system parameter ψ, a delegation warrant M_W, a message m, an ID and public key of an original signcrypter (OS), an ID and public key of a proxy signcrypter (PS), and a proxy key and outputs a proxy signcrypted ciphertext σ.

(x) **Proxy-Unsigncryption:** It inputs the system parameter ψ, a message M, a warrant M_W, an original signcrypter (OS)'s identity and public key, and a proxy signcrypter (PS)'s identity and public key. If the signature is verified to be correct, then it returns 1; otherwise, it returns 0.

2.2. Formal Security Model for CLPSC Scheme

2.2.1. Adversaries. In this section, we discuss two kinds of adversaries in the CLPSC schemes, as well as the types of oracle queries the adversaries have access to.

Type I adversary A_1 is a dishonest user who has the ability to replace public key, but A_1 is not capable of obtaining the system master key. Type II adversary A_2 is a malicious-but-passive KGC. This adversary can access the master key and generates the partial private key of users, but it is not able to replace the public key. Now, we describe eight oracle queries that can be accessed by both adversaries:

(i) **Create-User-Oracle:** This oracle inputs a users' identity ID. If the ID exists, then PK_{ID} of the corresponding ID is returned. Otherwise, it generates the private key $SK_{ID} = (d_{ID}, s_{ID})$ and the public key

$PK_{ID} = (P_{ID}, K_{ID})$, adds (ID, SK_{ID}, PK_{ID}) to the list L, and returns PK_{ID}.

(ii) **Reveal-Partial-Private-Key-Oracle:** This oracle looks for list L of an input users' ID. If the ID exists and then returns the corresponding d_{ID}. Otherwise, it return null.

(iii) **Reveal-Secret-Key-Oracle:** This oracle looks for list L of an input users' ID. If the ID exists, then returns the corresponding s_{ID}. Otherwise, returns null.

(iv) **Replace-Public-Key-Oracle:** This oracle can pick a random value instead of the users' public key. Upon receiving the target ID, the oracle replaces a corresponding public key in the list L.

(v) **Generate-Delegation-Oracle:** Upon receiving the system parameter ψ, an original signers private key $SK_{ID} = (d_{ID}, s_{ID})$, and a warrant M_W, this oracle can generate a delegation and send to the proxy signcrypter at a later stage.

(vi) **Proxy-Key-Oracle:** This oracle takes an original signers identity ID_O, a proxy signers identity ID_P, and a warrant M_W as inputs and outputs the proxy key and sends it to the proxy signer.

(vii) **Proxy-Signcrypt-Oracle:** This oracle takes a message M, a warrant M_W, an original signers identity ID_O, and a proxy signers' identity ID_P as inputs and generates a proxy signature σ_{ID_P} as an output.

(viii) **Proxy-Unsigncrypt-Oracle:** This oracle takes the system parameter ψ, the delegation warrant M_W, the signcrypted message δ, the public keys PK_{ID} and ID of the original user and the proxy signer, and the private key SK_{ID} of the receiver as inputs and checks if the delegation warrant M_W is valid. If the verification is true, then it unsigncrypts signcrypted message δ and returns a plaintext m. Otherwise it returns error.

2.2.2. Security Notions

(i) **Confidentiality**

(1) **Definition1**: A certificateless signcryption scheme has ciphertext indistinguishability (IND-CLSC-CCA2) for adaptive selective ciphertext attacks, only if no attacker has no unfair advantage in winning the following games 1 and 2 in polynomial bounded time.

(2) **Game 1 IND-CCA**: This game captures the confidentiality requirement, based on the indistinguishability of encryptions under adaptively chosen ciphertext attacks against A_1.

(3) **Initialization**: Upon receiving an input k, the setup algorithm is executed to get system parameters ψ and the master key s, then sends system parameters ψ to A_1, and keeps the system master key s secretly.

(4) **Phase I**: A_1 can ask for a polynomial bounded number of challenger queries from oracles.

(5) **Challenge**: A_1 submits three distinct identities: ID_O of original signcrypter, ID_P of proxy signcrypter, and ID_R of receiver and two equal length messages M_0 and M_1. The challenger chooses a random number $b \in \{0, 1\}$, proxy signcrypts M_b, to produce a corresponding signcrypted ciphertext δ^* to A_1.

(6) **Phase II**: A_1 can ask for similar queries from oracles as in Phase I, except for Reveal-Partial-Private-Key-Oracle and Reveal-Secret-Key-Oracle with receiver's identity, Proxy-Unsigncrypt-Oracle with $(\delta^*, ID_O, ID_P, ID_R)$, unless their public key has been changed.

(7) **Output**: At last, A_1 outputs $M_{b'}$ as the response of signcrypts δ^*. if $b' = b$, A_1 succeeds in the game.

(8) **Game 2 IND-CCA**: The game captures confidentiality requirements, based on the indistinguishability of encryptions under adaptively chosen ciphertext attacks against the adversary A_2.

(9) **Initialization**: Upon receiving an input k, the setup algorithm is executed to obtain the system parameter ψ and the system master key s and then sends them to A_2.

(10) **Phase I**: A_2 can ask for a polynomial bounded number of challenger queries from oracles.

(11) **Challenge**: A_2 submits three distinct identities: ID_O of original signcrypter, ID_P of proxy signcrypter, and ID_R of receiver and two equal length messages M_0 and M_1. The challenger chooses a random number $b \in \{0, 1\}$, proxy signcrypts M_b, to produce a corresponding signcrypted ciphertext δ^* to the adversary A_2.

(12) **Phase II**: A_2 can ask for similar queries from oracles as in Phase I, not including Proxy-Unsigncrypt-Oracle as before.

(13) **Output**: At last, A_2 outputs $M_{b'}$ as the response of signcrypts δ^*. if $b' = b$, A_2 succeeds in the game.

(ii) **Unforgeability**

(1) **Definition 2**: The CLPSC scheme is EUF-CMA secure only if no attacker has an unfair advantage in winning the following games 3 and 4 in the polynomial bounded time.

(2) **Game 3 EUF-CMA**: In this game, the adversary needs to successfully fabricate a valid ciphertext without any delegation warrant.

(3) **Initialization**: Upon receiving an input k, the setup algorithm is executed to generate the system parameter ψ, the system master key s, and then sends system parameters ψ to A_1 but keeps the system master key s secretly.

(4) **Queries**: A_1 can ask for a polynomial bounded number of challenger queries from oracles,

including Create-User-Oracle, Reveal-Partial-Private-Key-Oracle, Reveal-Secret-Key-Oracle, Replace-Public-Key-Oracle, Generate-Delegation-Oracle, Reveal-Proxy-Key-Oracle, Proxy-Signcrypt-Oracle, and Proxy-Unsigncrypt-Oracle.

(5) **Forgery**: At last, A_1 outputs a signcryption δ^* on message M under ID_{O^*}, ID_{P^*}. If δ^* is a valid ciphertext in Proxy-Signcrypt-Oracle and then A_1 succeeds in this game. However, A_1 is not permitted to query the Reveal-Partial-Private-Key oracle, the Replace-Public-Key oracle, or the Reveal-Secret-Key oracle of the original user in the game.

(6) **Game 4 EUF-CMA**: In the game, the challenger interacts with A_2 as follows:

(7) **Initialization**: Upon receiving an input k, the setup algorithm is executed to get system parameters ψ and a system master key s which are sent to A_2 later.

(8) **Queries**: A_2 may make adaptively a polynomial bounded number of queries to oracles like Create-User, Reveal-Secret-Key, Generate-Delegation, Reveal-Proxy-Key, Proxy-Signcrypt, and Proxy-Unsigncrypt through the challenger.

(9) **Forgery**: At last, A_2 outputs a signcryption δ^* on message M under ID_{O^*}, ID_{P^*}. If δ^* is a valid ciphertext in Proxy-Signcrypt-Oracle, then A_1 succeeds in this game. It is mandatory that A_2 has not queried Reveal-Secret-Key oracle during the game.

3. Review and Analysis of Bhatia and Verma's CLPSC Scheme

3.1. Review of Bhatia and Verma's CLPSC Scheme. In this section, we review the scheme of Bhatia and Verma, which consists of the following 10 polynomial time algorithms.

Setup. After the key generation center (KGC, who has the responsibility for system keys and the partial private keys of users) has chosen a security parameter k, the algorithm performs the following steps:

(1) Chooses an elliptic curve E/E_p over prime finite field F_p

(2) Chooses a cyclic subgroup G of the elliptic curve group, sets P as a generator of order q

(3) Chooses a master secret key $s \in Z_q^*$ and generates $P_{pub} = sP$ as a master public key

(4) Lets the message space be $\{0,1\}^l$ and selects four different hash functions H_1, H_2, H_3, H_4:

$$H_1 : \{0,1\}^* \times G \longrightarrow Z_q^*$$
$$H_2 : \{0,1\}^* \times G \times G \times G \times G \longrightarrow Z_q^*$$
$$H_3 : G \longrightarrow \{0,1\}^l$$
$$H_4 : \{0,1\}^* \longrightarrow Z_q^* \quad (1)$$

(5) At last, outputs the system parameters $\psi = \{E, F_p, G, P, H_1, H_2, H_3, H_4, P_{pub}\}$.

Extract-Partial-Private-Key. Taking the system parameters ψ, system private key s, and ID_O as inputs, KGC can calculate the partial private key $d_O = k_O + h_O s$ of user O, where $k_O \in Z_q^*$ is randomly chosen. Then, $K_O = k_O P, h_O = H_1(ID_O, K_O), (d_O, K_O)$ are sent to the user in a secure communication channel.

Set-Secret. Upon receiving (d_O, K_O), the user O verifies whether the parameters come from a legitimate KGC by computing $d_O P = K_O + h_O P_{pub}$. After successful verification, O picks a random s_O as its secret value and computes $P_O = s_O P$.

Set-Private-Key. Given system parameters, partial private key d_O, and secret value s_O as inputs, this algorithm outputs a private key pair $SK_O = (s_O, d_O)$.

Set-Public-Key. Given system parameters ψ, P_O, K_O as inputs, this algorithm outputs a public key pair $PK_O = (P_O, K_O)$.

Gen-Delegation. Having the inputs, the original signcrypters private key pair $SK_O = (s_O, d_O)$, public key pair $PK_O = (P_O, K_O)$, and message warrant M_W, this algorithm generates the delegation $D_{O \longrightarrow P}$ on M_W. Then, the user O randomly chooses $a \in Z_q^*$, computes $K = aP$, and further computes t as follows:

$$t = (a + h_1 (d_O + s_O)), \quad (2)$$

where $h_1 = H_2(M_W \parallel ID_P, K, K_O, P_O, P_{pub})$. The delegation $D_{O \longrightarrow P} = (ID_O, ID_P, M_W, K, K_O, P_O, t)$ is sent to the proxy signcrypter (PS) later.

Verify-Delegation. The PS verifies whether the delegation is legitimate by computing

$$h_1 = H_2 \left(M_W \parallel ID_P, K, K_O, P_O, P_{pub}\right)$$
$$h_O = H_1 (ID_O, K_O) \quad (3)$$

and checks whether

$$tp = h_1 \left(K_O + h_O P_{pub} + P_O\right) \quad (4)$$

If not, the proxy signcrypter rejects the delegation request.

Gen-Proxy-Key. Upon successful verification, PS computes a proxy signing key

$$D_P = (t + h_2 (d_P + s_P)), \quad (5)$$

where $h_2 = H_2(M_W \parallel ID_O, K, K_P, P_P, P_{pub})$.

Proxy-Signcryption. Given proxy key D_P, message M, and public key of the receiver (P_R, K_R) as inputs, it generates a signcrypted ciphertext on O's behalf. Specifically, PS randomly chooses $u \in Z_q^*$ and further calculates $U = uP, V = uP_R, h = H_3(V), h_3 = H_4(M \parallel ID_O \parallel ID_R \parallel ID_P)$. The detail processes of generating proxy signcryption on message M are described as follows:

$$z = M \oplus h \tag{6}$$

$$S = (u + h_3 D_P) \tag{7}$$

After that, the signcrypted ciphertext $(ID_O, K_O, P_O, M_W, ID_P, K_P, P_P, U, K, z, S)$ is sent to R by PS.

Proxy-Unsigncryption. After receiving a complete signcrypted ciphertext $(ID_O, K_O, P_O, M_W, ID_P, K_P, P_P, U, K, z, S)$, the receiver R unsigncrypts $V = s_R U, M = z \oplus H_3(V)$ and

$$SP = h_3 \left[K + h_1 \left(K_O + P_O + h_O P_{pub}\right)\right] + h_2 \left(K_P + P_P + h_C P_{pub}\right)\Big] + U \tag{8}$$

If the above equation holds, then R accepts the message.

3.2. Analysis of Bhatia and Verma's CLPSC Scheme. We will now present a successful public key replacement attack by a Type 1 adversary A_1 against the scheme.

Step 1. A_1 chooses three random numbers $a^* \in Z_q^*, z_1 \in Z_q^*, z_2 \in Z_q^*$ and computes

$$K' = a'P \tag{9}$$

$$K_O' = z_1 P \tag{10}$$

$$P_O' = z_2 P - h_O' P_{pub} \tag{11}$$

$$h_O' = H_1\left(ID_O, K_O'\right) \tag{12}$$

Then, it generates a forged public key pair K_O', P_O' and substitutes the original public key of OS.

Step 2. Given a message warrant M_W', which can be intercepted from the communication channel between OS and PS, OS computes $t' = (a' + h_1'(z_1 + z_2))$, where $h_1' = H_2(M_W \parallel ID_P, K', K_O', P_O', P_{pub})$. Then, it sends the delegation $D_{(O \longrightarrow P)} = (ID_O, ID_P, M_W', K', K_O', P_O', t')$ to the proxy signcrypter (PS).

Step 3. After PS receives $D_{(O \longrightarrow P)}$, it computes $h_1' = H_2(M_W \parallel ID_P, K', K_O', P_O', P_{pub})$ and $h_O' = H_1(ID_O, K_O')$ to verify the delegation. Then, it checks whether $t'P = h_1'(K_O' + h_O' P_{pub} + P_O') + K'$. Note that

$$\begin{aligned} t'P &= \left(a' + h_1'\left(z_1 + z_2\right)\right)P \\ t'P &= a'P + h_1' z_1 P + h_1' z_2 P \end{aligned} \tag{13}$$

According (10), (11), and (12), we compute

$$\begin{aligned} t'P &= K' + h_1' K_O' + h_1'\left(P_O' + h_O' P_{pub}\right) \\ t'P &= K' + h_1'\left(K_O' + P_O' + h_O' P_{pub}\right) \end{aligned} \tag{14}$$

By using the above K', K_O', P_O', t' from A_1 to the proxy signcrypter, the verification is successful. In other words, the delegation $D_{(O \longrightarrow P)}$ in the scheme of Bhatia and Verma can be forged.

Given the linear relationship between d_O and s_O in the equation, the adversary can use a fake public key to bypass the process of verify-delegation. Specifically, the adversary forges the fake secret key and computes the fake public key, because there is no equation to verify or bind the public key (K_O, P_O) in the verification process. Therefore, in our improved CLPSC scheme, we construct a hash function h_s that contains P_O as the coefficient of s_O. If the adversary executes the public key replacement attack, then the adversary will need to randomly choose $s_O{}' \in Z_q^*$ and the coefficient h_s' will be changed too. This prevents the forgery of P_O'.

4. Proposed CLPSC Scheme

Here, we present our proposed scheme that consists of the following three basic components: prescriber (e.g., a medical practitioner), transaction hub, and pharmacy that has implemented the electronic prescription system. Patient's medical information (e.g., patient's medical record, medication history) is stored in the database. The prescriber can find this information by searching on the database using the patient's unique information, such as names, dates of birth, and current addresses. Once the record is found, the doctor can update or upload a new prescription recording new medical information to the server after reviewing it (see Figure 1). The transaction hub works like a database for recording the patient file or all prescriptions. After downloading the patients prescription and successfully executing the proxy-unsigncryption, the pharmacy will dispense the medication listed in the electronic prescription to the proxy signcrypter.

Now, we describe how to send the proxy delegation from the original signcrypter OS to the proxy signcrypter PS securely.

(i) **Setup**: KGC picks a security parameter $s \in Z_q^*$ as an input of this algorithm. After running this algorithm, system parameters $\psi = E, F_p, G, P, H_1, H_2, H_3, H_4, P_{pub}$ will be published, where E/Ep is an elliptic curve chosen by KGC over prime finite field Fp, G is a cyclic subgroup of the elliptic curve group, P is a generator of G, q is the order of G, and $P_{pub} = sP$ can be easily computed. In addition, there are four cryptographic collision resistant hash functions as follows:

$$H_1 : \{0,1\}^* \times G \longrightarrow Z_q^*$$

$$H_2 : \{0,1\}^* \times G \times G \times G \longrightarrow Z_q^*$$

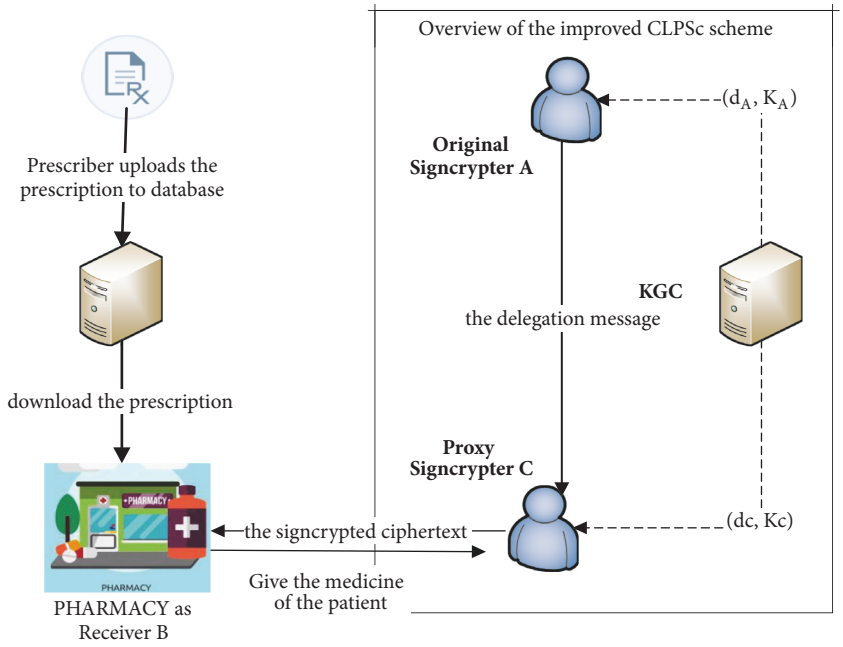

Figure 1: Improved CLPSC scheme for electronic prescription system.

$$H_3 : G \longrightarrow \{0,1\}^l$$
$$H_4 : \{0,1\}^* \longrightarrow Z_q^* \tag{15}$$

The message space is $\{0,1\}^l$.

(ii) **Extract-Partial-Private-Key**: This algorithm takes system parameters ψ, system private key s, and user O's identity ID_O as inputs and computes $d_O = k_O + h_O s$ to obtain the extract-partial-private-key of entity O, where $k_O \in Z_q^*$ is randomly chosen. $K_O = k_O P, h_O = H_1(ID_O, K_O)$ is computed, and the results (d_O, K_O) are sent to entity O via a secure communicate channel (this algorithm is run by the KGC.)

(iii) **Set-Secret**: This algorithm takes system parameters ψ, user O's identity ID_O as inputs and runs to verify whether $d_O P = K_O + h_O P_{pub}$. If the verification passes, then entity O picks a random $s_O \in Z_q^*$ as its secret value and computes its partial public key $P_O = s_O P$; otherwise, the process fails (his algorithm is run by users).

(iv) **Set-Private-Key**: This algorithm takes system parameters ψ, partial private key d_O, and secret value s_O as inputs and generates a private key pair $SK_O = (s_O, d_O)$ as the output (this algorithm is run by users.)

(v) **Set-Public-Key**: Given system parameters ψ, P_O, and K_O as inputs, this algorithm generates a public key pair $PK_O = (P_O, K_O)$ as the output. When this algorithm completes executing, user publishes the public key PK_O (this algorithm is run by users.)

(vi) **Gen-Delegation**: Given the original signcrypters private key pair $SK_O = (s_O, d_O)$, public key pair $PK_O = (P_O, K_O)$, and message warrant M_W as input, this algorithm generates the delegation $D_{O \longrightarrow P}$ on M_W as the output. Then, the entity O randomly chooses $a \in Z_q^*$, computes $K = aP$ and computes t as follows: $t = (a + h_1(d_O + s_O h_s))$, where $h_1 = H_2(M_W \parallel ID_P, K, K_O, P_O, P_{pub}), h_s = H_1(ID_O, P_O)$. The delegation $D_{O \longrightarrow P} = ID_O, ID_P, M_W, K_O, P_O, t$ is finally sent to PS.

(vii) **Verify-Delegation**: PS verifies whether the delegation is valid by computing

$$h_1 = H_2\left(M_W \parallel ID_P, K, K_O, P_O, P_{pub}\right)$$
$$h_O = H_1\left(ID_O, K_O\right) \tag{16}$$
$$h_s = H_1\left(ID_O, P_O\right)$$

and checks whether

$$tp = h_1\left(K_O + h_O P_{pub} + h_s P_O\right) + K \tag{17}$$

If the following does not hold, then it implies that the delegation is invalid.

(viii) **Gen-Proxy-Key**: Upon successful verification, PS generates a proxy signing key $D_P = (t + h_2(d_P + s_P))$, where $h_2 = H_2(M_W \parallel ID_O, K, P_P, K_P, P_{pub})$

(ix) **Proxy-Signcryption**: Given the proxy key D_P, an original message M, and the receiver's public key P_R, K_R as inputs, a signcrypted message is generated for R. The following describe the details: PS randomly chooses $u \in Z_q^*$, computes $U = uP, V = uP_R, h = H_3(V), h_3 = H_4(M \parallel ID_O \parallel ID_P \parallel ID_R)$, and the proxy signcryption of message M is generated

as follows: $z = M \oplus h, S = (u + h_3 D_P)$. After that the signcrypted ciphertext $(ID_O, K_O, P_O, M_W, ID_P, K_P, P_P, U, K, z, S)$ is sent to the receiver R by PS.

(x) **Proxy-Unsigncryption**: Upon receiving the signcrypted ciphertext $(ID_O, K_O, P_O, M_W, ID_P, K_P, P_P, U, K, z, S)$, R calculates $V = s_R U, M = z \oplus H_3(V)$, and only if the following holds, will R accept the message:

$$SP = h_3 \left[K + h_1 \left(K_O + P_O + h_O P_{pub}\right)\right] + h_2 \left(K_P + P_P + h_P P_{pub}\right)\Big] + U \tag{18}$$

4.1. Correctness Analysis. The CLPSC scheme contains two parts of authentication, namely, verification of delegation (i.e., proxy signcrypter PS checks whether $tp = h_1(K_O + h_O P_{pub} + h_s P_O) + K$) and proxy-unsigncryption (i.e., message receiver checks whether $SP = h_3[K + h_1(K_O + h_s P_O + h_O P_{pub}) + h_2(K_P + P_P + h_P P_{pub})] + U$).

(i) **Decryption process**

$$V' = s_R U' = s_R uP = uP_R = V \tag{19}$$

(ii) **Verification process**

One part is

$$\begin{aligned} t &= \left(a + h_1 \left(d_O + s_O h_s\right)\right) \\ tP &= \left(a + h_1 \left(d_O + s_O h_s\right)\right) P \\ &= \left(aP + h_1 \left(d_O P + s_O h_s P\right)\right) \\ &= \left(K + h_1 \left(\left(k_O + h_O s\right) P + h_s P_O\right)\right) \\ &= \left(K + h_1 \left(\left(k_O P + h_O s P + h_s P_O\right)\right)\right) \\ &= \left(K + h_1 \left(\left(K_O + h_O P_{pub} + h_s P_O\right)\right)\right) \end{aligned} \tag{20}$$

Another part is

$$\begin{aligned} SP &= \left(u + h_3 D_P\right) P \\ SP &= uP + h_3 \left(t + h_2 \left(d_P + s_P\right)\right) P \\ SP &= h_3 \left(tP + h_2 \left(d_P P + s_P P\right)\right) + U \\ SP &= h_3 \left(tP + h_2 \left(d_P P + s_P P\right)\right) + U \\ SP &= h_3 \left[K + h_1 \left(K_O + h_s P_O + h_O P_{pub}\right)\right. \\ &\quad \left. + h_2 \left(K_P + P_P + h_P P_{pub}\right)\right] + U \end{aligned} \tag{21}$$

5. Security Analysis

As defined in Section 2.2, there are two types of adversaries: $\mathcal{A}_1$ and $\mathcal{A}_2$. We consider four games where $\mathcal{A}_1$ and $\mathcal{A}_2$ can get honest answer when they interact with the challenger.

5.1. Confidentiality. We define the fact that the certificateless signcryption scheme is IND-CLSC-CCA2-secure to adaptive chosen ciphertext attacks, only if no attacker with a nonnegligible advantage can win the games in polynomial time.

Game 1. In this game, we assume that $\mathcal{A}_1$ is a dishonest user.

Lemma 1. *Assume that $\mathcal{A}_1$ can break the proposed CLPSC scheme with v'. Let q_{H_i}, q_{C_u}, $q_{P_{pk}}$, q_{S_k}, $q_{R_{pk}}$, q_{G_d}, $q_{P_r k}$, q_{S_c}, and $q_{U_{sc}}$ denote the number of H_i-queries, Create-User-queries, Reveal-Partial-Private-Key-queries, Reveal-Secret-Key-queries, Replace-Public-Key-queries, Generate-Delegation-queries, Reveal-Proxy-Key-queries, Proxy-Signcrypt-queries, and Proxy-Usigncrypt-queries, respectively. There is an algorithm that can solve the ECCDH problem with advantage v' in probabilistic polynomial time:*

$$\begin{aligned} v' &\geq \frac{1}{q_{H_3}} \left(2v - q_{U_{sc}} \left(\frac{1}{2}\right)^l\right) \\ t' &\leq t + O(1) \left(q_{H_1}, q_{H_2}, q_{H_3}, q_{H_4}, q_{C_u}, q_{P_{pk}}, q_{S_k}, q_{R_{Pk}}, q_{G_d}, \right. \\ &\quad \left. q_{P_r k}, q_{S_c}, q_{U_{sc}} + t_M \left(2q_{C_u} + q_{P_p k} + 2q_{S_c} + 7q_{U_s c}\right)\right) \end{aligned} \tag{22}$$

where t_M is the time for an ECC-based scalar point multiplication operation.

Proof. Suppose that an algorithm accepts an ECCDH instance $(P, xP, yP) \in G_q$ with unknown x and y; the problem is to compute xyP. In order to solve this problem, the algorithm uses A_1 as a subroutine and acts as a challenger $\mathcal{C}$ to interact with it in IND-CCA2-I. When the game starts, the challenger $\mathcal{C}$ creates and maintains $L_{H_1}, L_{H_2}, L_{H_3}, L_{H_4}, L_1, L_{PK}, L_{Sc}$ lists, which stores the responses to the queries by the adversary A_1. The lists are initially set to be empty. When A_1 makes a query, $\mathcal{C}$ will respond as follows:

(i) H_1-**Query**: $\mathcal{C}$ maintains a hash list $L_{H_1} =< (ID, K_{ID}), , z_1 >$ as explained below. When A_1 asks for the H_1-Query-Oracle and if the query ID is found in L_{H_1}, then the algorithm returns the record to A_1. Otherwise, $\mathcal{C}$ chooses a random number $z_1 \in Z_q^*$ and adds it to L_{H_1}.

(ii) H_2-**Query**: $\mathcal{C}$ maintains a hash list $L_{H_2} =< (M_W \parallel ID_P, K, K_O, P_O, P_{pub}), z_2 >$ as explained below. When A_1 asks for the H_2-Query-Oracle and if the tuple is found in L_{H_2}, then the algorithm returns z_2 to A_1. Otherwise, $\mathcal{C}$ chooses a random number $z_2 \in Z_q^*$ and adds $< (M_W \parallel ID_P, K, K_O, P_O, P_{pub}), z_2 >$ to L_{H_2}.

(iii) H_3-**Query**: $\mathcal{C}$ maintains a hash list $L_{H_3} =< V, z_3 >$ as explained below. When A_1 asks for the H_3-Query-Oracle and if the tuple $< V, z_3 >$ is found in L_{H_3}, then the algorithm returns z_3 to A_1. Otherwise, $\mathcal{C}$ chooses a random number $z_3 \in \{0,1\}^l$ and adds it to L_{H_3}.

(iv) H_4-**Query**: $\mathcal{C}$ maintains a hash list $L_{H_3} =< (M \parallel ID_O \parallel ID_P \parallel ID_R), z_4 >$ as explained below. When A_1 asks for the H_4-Query-Oracle and if the tuple is

found in L_{H_4}, then the algorithm returns z_4 to A_1. Otherwise, $\mathscr{C}$ chooses a random number $z_4 \in Z_q^*$ and adds it to L_{H_4}.

(v) **Create-User query**: $\mathscr{C}$ maintains a list L_c =< $ID, K_{ID}, P_{ID}, s_{ID}, d_{ID}$ >. If the query ID is found on the L_c, then it returns < $ID, K_{ID}, P_{ID}, s_{ID}, d_{ID}$ >. Otherwise, the oracle is simulated as follows:

(1) $\mathscr{C}$ choosing three numbers $s_O, k_O, z_1 \in Z_q^*$ randomly
(2) computing $P_O = s_O P, K_O = k_O P, d_O = k_O + z_1 s$
(3) adding the tuple $\langle ID_O, K_O, s_O, d_O\rangle$ to list L_C and $\langle (ID_O, K_O), z_1\rangle$ to L_{H_1}, respectively.

(vi) **Extract-Partial-Private-Key-Query**: When A_1 queries d_{ID} and if $ID = ID^*$, then the simulation is stopped. Otherwise, $\mathscr{C}$ probes the list L_c for the query ID. If it exists on L_c, then it returns the corresponding d_{ID}. Otherwise, $\mathscr{C}$ performs the Create-User query, gets < $ID, K_{ID}, P_{ID}, s_{ID}, d_{ID}$ >, and sends its partial private key d_{ID} to A_1.

(vii) **Reveal-Secret-Key-Query**: If $ID = ID^*$, then the simulation is stopped. Otherwise, $\mathscr{C}$ probes the list $L_c$for the query ID. If it exists on L_c, then it returns the corresponding s_{ID}. Otherwise, $\mathscr{C}$ performs the Create-User query and sends its partial private key s_{ID} to A_1.

(viii) **Replace-Public-Key-Query**: A_1 can replace the public key $PK_{ID} = (P_{ID}, K_{ID})$ with a random value PK'_{ID}.

(ix) **Generate-Delegation-Query**: When A_1 asks the Generate-Delegation query on (ID_O, ID_P, M_W), $\mathscr{C}$ starts to run the Gen-Delegation algorithm and sends the results $D_{O\longrightarrow P} = ID_O, ID_P, M_W, K_O, P_O, a, t$ to A_1.

(x) **Reveal-Proxy-Key-Query**: $\mathscr{C}$ maintains a list of issued proxy keys $L_{P_k} = ID_O, ID_P, M_W, a, K, t, D_P$. If the query (ID_O, ID_P, M_W) exists on the L_{P_k}, then it returns a proxy key D_P. Otherwise, $\mathscr{C}$ works as follows:

(1) performing Generate-Delegation-Query to obtain $D_{O\longrightarrow P} = ID_O, ID_P, M_W, K_O, P_O, a, t$.
(2) querying the list L_1 with ID_P for the corresponding secret key (s_P, d_P).
(3) computing $D_P = (t + z_2(d_P + s_P))$ and adds the tuple $\langle ID_O, ID_P, M_W, K, a, t, D_P\rangle$ to list $L_(P_k)$. Finally, it sends D_P to A_1.

(xi) **Proxy-Signcrypt-Query**: When A_1 makes a query for signcrypting a message M with the message warrant M_W and three input identities (ID_O, ID_R, ID_P) and if the query entry (ID_O, ID_P, M_W) exists on list L_{P_k}, then the corresponding proxy key D_P and K on the tuple can be used by $\mathscr{C}$ to create a signcrypted message δ. Otherwise, $\mathscr{C}$ performs the aforementioned Reveal-Proxy-Key query to obtain the proxy key D_P. To generate a signcrypted message on behalf of an original signer, $\mathscr{C}$ checks whether ID_O and ID_R are correct. If not, the proxy-signcryption algorithm is run until the secret key (s_O, d_O) of user O is obtained. Then, the tuple $\langle ID_O, PK_O, M_W, ID_R, PK_R, M, \delta\rangle$ is added to L_{S_c} as the result. Otherwise, $\mathscr{C}$ performs the following:

(1) choosing random numbers $x, z_4 \in Z_q^*$ and computing $U = xP, V = xyP$.
(2) probing L_{H_3} for (V) and returning z_3 as a result.
(3) computing $z = M \oplus z_3 S = (x + z_4 D_P)$ and adding a tuple $\langle ID_O \parallel ID_R \parallel ID_P, M_W\rangle$ to list L_{H_4}, where $L_{H_4} \parallel ID_O \parallel ID_R \parallel ID_P = z_4$

(xii) **Proxy-Unsigncrypt-Query**: Taking the signcrypted message $\delta = (ID_O, P_O, K_O, M_W, ID_P, P_P, K_P, U, K, z, S)$ as inputs, $\mathscr{C}$ checks if ID_R is a challenging identity. If it is true, $\mathscr{C}$ probes L_{S_p} for an tuple $\langle ID_O, PK_O, ID_R, PK_R, *, \delta\rangle$ and obtains the corresponding plaintext message M. Otherwise, $\mathscr{C}$ performs as follows:

(1) taking the secret key of the receiver as an input and calculating $V = s_R U$.
(2) probing L_{H_3} for (V) and returning z_3 to calculate $M = z \oplus z_3$.
(3) probing the list L_{H_1} for (ID_O, K_O) and (ID_P, K_P), $L_{H_2}$for $(ID_P \parallel M_W, K, K_O, P_O, P_{pub})$ and $(ID_P \parallel M_W, K, K_P, P_P, P_{pub})$ and L_{H_4} for $ID_O \parallel ID_R \parallel ID_P, M_W$, to get z_1, z_1', z_2, z_2', and z_4 respectively. If $SP = z_4[K + z_2(K_O + h_s P_O + h_O P_{pub}) + z_2'(K_P + P_P + z_1' P_{pub})] + U$ is valid, $\mathscr{C}$ returns M. Otherwise, it throws an error message.

□

Challenge. A_1 submits three distinct identities: ID_O of original signcrypter, ID_P of proxy signcrypter, and ID_R of receiver and two equal length messages M_0 and M_1. A random number $b \in \{0, 1\}$ is chosen by $\mathscr{C}$. What is more, $\mathscr{C}$ signcrypts M_b to produce a corresponding signcrypted ciphertext δ^* to A_1. $\mathscr{C}$ further probes L_{p_k} for L_{p_k} to obtain z_3^*, calculates $z^* = M_b \oplus z_3^*, S^* = x + z_3^* D_P^*$, and adds $(M_b \parallel ID_O^* \parallel ID_P^* \parallel ID_R^*, z_4^*)$ to the list. Finally, a signcrypted message $\delta^* = (ID_O^*, K_O^*, P_O^*, M_W^*, ID_P^*, K_P^*, P_P^*, U^*, K^*, z^*, S^*)$ for M_b is returned by $\mathscr{C}$ to A_1. $\mathscr{C}$ can continue to ask queries with the exception of the Proxy-Unsigncrypt query on δ^*, Reveal-Partial-Private-Key-query, and Reveal-Secret-Key-query in the game.

Output. At last, $\mathscr{A}_1$ outputs b' as the guess of value b. If $b' = b$, then $\mathscr{C}$ outputs $V = s_R U = s_R uP$ as the solution of the ECCDH question; otherwise, the challenge fails.

Game 2. Let $\mathscr{A}_2$ be a malicious-but-passive KGC.

Lemma 2. *Assume that $\mathscr{A}_2$ has the ability of breaking the proposed CLPSC scheme with an advantage of v'. Let q_{H_i},*

q_{C_u}, $q_{P_{pk}}$, q_{S_k}, q_{G_d}, $q_{P_r k}$, q_{S_c}, and $q_{U_s c}$ denote the number of H_i-queries, Create-User-queries, Reveal-Partial-Private-Key-queries, Reveal-Secret-Key-queries, Generate-Delegation-queries, Reveal-Proxy-Key-queries, Proxy-Signcrypt-queries, and Proxy-Usigncrypt-queries, respectively. In probabilistic polynomial time, there is an algorithm which can solve ECCDH problem with advantage v':

$$\begin{aligned} v' &\geq \frac{1}{q_{H_3}}\left(2v - q_{U_s c}\left(\frac{1}{2}\right)^l\right) \\ t' &\leq t + O(1)\left(q_{H_1} + q_{H_2} + q_{H_3} + q_{H_4} + q_{C_u} + q_{P_{pk}}\right. \\ &\quad + q_{S_k} + q_{R_{Pk}} + q_{G_d} + q_{P_r k} + q_{S_c} + q_{U_{sc}} \\ &\quad \left. + t_M\left(2q_{C_u} + 2q_{S_c} + 7q_{U_s c}\right)\right) \end{aligned} \tag{23}$$

where t_M is the time for an ECC-based scalar point multiplication operation.

Proof. The proof for this game is similar to that of Game 1, and hence we will not repeat the proof. □

5.2. Unforgeability. We defined that the certificateless signcryption scheme is EUF-CMA-secure to adaptive chosen ciphertext attacks, only if no attacker with a nonnegligible advantage can win the following games in polynomial time.

Game 3. Assume that $\mathcal{A}_1$ is a dishonest user.

Lemma 3. *Assume that $\mathcal{A}_1$ can break the proposed CLPSC scheme with v'. Let q_{H_i}, q_{C_u}, $q_{P_{pk}}$, q_{S_k},$q_{R_{pk}}$, q_{G_d}, $q_{P_r k}$, and q_{S_c} denote the number of H_i-queries, Create-User-queries, Reveal-Partial-Private-Key-queries, Reveal-Secret-Key-queries, Generate-Delegation-queries, Reveal-Proxy-Key-queries, and Proxy-Signcrypt-queries, respectively. There is an algorithm in probabilistic polynomial time that can solve ECCDH problem with advantage v':*

$$\begin{aligned} v' &\geq \frac{1}{q_{H_3} q_{H_4}}\left(v - \left(1 + q_{H_4}\right)\left(\frac{1}{2}\right)^l\right) \\ t' &\leq t + O(1)\left(q_{H_1} + q_{H_2} + q_{H_3} + q_{H_4} + q_{C_u} + q_{P_{pk}}\right. \\ &\quad + q_{S_k} + q_{R_{Pk}} + q_{G_d} + q_{P_r k} + q_{S_c} + q_{U_{sc}} \\ &\quad \left. + t_M\left(2q_{C_u} + q_{P_p k} + 2q_{S_c}\right)\right) \end{aligned} \tag{24}$$

where t_M is the time for an ECC-based scalar point multiplication operation.

Proof. Suppose that an algorithm accepts an ECCDH instance $(P, xP, yP) \in G_q$ with unknown x and y; the problem is to compute xyP. In order to solve this problem, the algorithm uses A_1 as a subroutine and acts as a challenger $\mathcal{C}$ to interact with it. $\mathcal{C}$ gives honest answer to the queries of A_1. When the game starts, the relevant system parameters are created and sent to A_1 by $\mathcal{C}$. We set $P_{pub} = xP$. Then, A_1 can make queries for information. The challenger $\mathcal{C}$ creates and maintains $L_{H_1}, L_{H_2}, L_{H_3}, L_{H_4}, L_1, L_{PK}, L_{Sc}$ lists, which store the returns of the responses to the adversary's queries. The lists are initially set to be empty. □

Forgery. At last, a signcrypted ciphertext $\delta^* = (ID_A^*, K_A^*, P_A^*, M_W^*, ID_P^*, K_P^*, P_P^*, U^*, K^*, z^*, S^*)$ on message M and warrant M_W^* is produced as the output, where ID_A^* is the original signer and ID_R^* is the receiver. Unlike normal cases, it does not go through the ProxySigncrypt oracle. ID_P^* is a forge ID as a proxy signer for ID_A^*. A_1 takes this signcrypted ciphertext δ^* as an input of the Proxy-Unsigncrypt oracle and makes queries to $\mathcal{C}$ except for Reveal-Partial-Private-Key-Oracle and Replace-Public-Key-Oracle or Reveal-Secret-Key-Oracle in probabilistic polynomial time. If Proxy-Unsigncrypt-Oracle is not an error, then A_1 succeeds in this game. Otherwise, A_1 fails. The solution of the problem is $x = (((D_c - t)/h_2) - k_c - s_c)/h_c$.

Game 4. Let $\mathcal{A}_2$ be a malicious-but-passive KGC.

Lemma 4. *Assume that $\mathcal{A}_2$ can break the proposed CLPSC scheme with v'. Let q_{H_i}, q_{C_u}, q_{S_k}, q_{G_d}, $q_{P_r k}$, and q_{S_c} denote the number of H_i-queries, Create-User-queries, Reveal-Partial-Private-Key-queries, Reveal-Secret-Key-queries, Generate-Delegation-queries, Reveal-Proxy-Key-queries, and Proxy-Signcrypt-queries, respectively. In probabilistic polynomial time, there is an algorithm that can solve ECCDH problem with advantage v':*

$$\begin{aligned} v' &\geq \frac{1}{q_{H_3} q_{H_4}}\left(v - \left(1 + q_{U_s c}\right)\left(\frac{1}{2}\right)^l\right) \\ t' &\leq t + O(1)\left(q_{H_1} + q_{H_2} + q_{H_3} + q_{H_4} + q_{C_u} + q_{S_k}\right. \\ &\quad + q_{G_d} + q_{P_r k} + q_{S_c} + q_{U_{sc}} + t_M\left(2q_{C_u} + 2q_{S_c}\right)\left.\right) \end{aligned} \tag{25}$$

where t_M is the time for an ECC-based scalar point multiplication operation.

Proof. The proof for this game is similar to that of Game 3, and hence we will not repeat the proof. □

6. Performance Evaluation

In this section, we compare the efficiency and security of our improved scheme with other proxy-signcryption schemes [15, 16] in the literature. We use the standard cryptographic library MIRACL [19] to measure the runtime, whose comparative summary is given in Table 1, where t_{pm} denotes an ECC-based point multiplication operation time and t_h denotes general hash operation time.

Our evaluation environment is a personal computer (PC; Dell with an I5-4460S 2.90GHz processor, 4G bytes memory and the Window 8 operating system) with the MIRACL library [20]. The curve is $E : y^2 + xy = (x^3 + ax^2 + b)$ over 163 bits random prime, where $a = 1$, $b = 1$. A Koblitz curve ect163k1 over $F_{(}2^{163})$ is selected from the list of elliptic

Table 1: Performance comparison.

Scheme	[15]	[16]	Our scheme
Proxy key generation	$7t_h$	$4t_h$	$6t_h$
Proxy-Signcryption	$5t_{pm} + 3t_h$	$2t_{pm} + 2t_h$	$2t_{pm} + 2t_h$
Proxy-Unsigncrytion	$10t_{pm} + 8t_h$	$7t_{pm} + 6t_h$	$7t_{pm} + 6t_h$
Total running time(ms)	33.276	19.974	19.988

Table 2: Security comparison.

Scheme	[15]	[16]	Our scheme
Security proof	no	yes	yes
Against forgery attack	no	no	yes

curves indicated by NIST [21]. In this setup, we have $t_{pm} = 2.21$, $t_h = 0.007$ approximately. Then, we compute the total runtime with their operation times. From Table 1, we observe that the runtime of [16] and our scheme are less than other schemes. Because our scheme is an improved scheme from [16], the runtime is very close to that of the original scheme. However, from Table 2, it is clear that our scheme is the most secure of these schemes. It is also trivial to note that the original scheme in [16] cannot resist forgery attack, unlike our scheme (at a slight cost of about 0.112 ms).

7. Conclusion

While signcryption is a fairly established research area, designing secure signcryption schemes remains challenging. For example, in this paper we revisited a recently proposed certificateless proxy-signcryption (CLPSC) scheme of Bhatia and Verma and revealed that the scheme is susceptible to the public key replacement attack by a Type 1 adversary. Then, we presented an improved scheme to mitigate such an attack from both Type 1 and Type 2 adversaries. We also evaluated its security and performance to demonstrate its utility in an electronic prescription system.

Future research includes implementing a prototype of the improved protocol for evaluation in a real-world environment.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of the paper.

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References

[1] M. Mäkinen, P. Rautava, J. Forsström, and M. Äärimaa, "Electronic prescriptions are slowly spreading in the European Union," *Telemedicine and e-Health*, vol. 17, no. 3, pp. 217–222, 2011.

[2] M. Samadbeik, M. Ahmadi, F. Sadoughi, and A. Garavand, "A copmarative review of electronic prescription systems: Lessons learned from developed countries," *Journal of Research in Pharmacy Practice*, vol. 6, no. 1, p. 3, 2017.

[3] K. L. Lapane, R. K. Rosen, and C. Dubé, "Perceptions of e-prescribing efficiencies and inefficiencies in ambulatory care," *International Journal of Medical Informatics*, vol. 80, no. 1, pp. 39–46, 2011.

[4] M. A. Fischer, M. R. Stedman, J. Lii et al., "Primary medication non-adherence: analysis of 195,930 electronic prescriptions," *Journal of General Internal Medicine*, vol. 25, no. 4, pp. 284–290, 2010.

[5] H. Brits, A. Botha, L. Niksch, R. Terblanché, K. Venter, and G. Joubert, "Illegible handwriting and other prescription errors on prescriptions at national district hospital, bloemfontein," *South African Family Practice*, vol. 59, no. 1, pp. 52–55, 2017.

[6] H.-Y. Lin, T.-S. Wu, S.-K. Huang, and Y.-S. Yeh, "Efficient proxy signcryption scheme with provable CCA and CMA security," *Computers & Mathematics with Applications*, vol. 60, no. 7, pp. 1850–1858, 2010.

[7] Y. Zheng, "Digital signcryption or how to achieve cost(signature encryption," in *Proceedings of the cost(signature) + cost(encryption) , in Advances in Cryptology - CRYPTO 97, 17th Annual International Cryptology Conference*, pp. 165–179, Santa Barbara, California, USA, 1997.

[8] R. Steinfeld and Y. Zheng, "A Signcryption Scheme Based on Integer Factorization," in *Proceedings of the Third International Workshop, ISW 2000, Wollongong, NSW, Australia*, Information Security, pp. 308–322, December, 2000.

[9] J. H. An, Y. Dodis, and T. Rabin, "On the security of joint signature and encryption," in *Proceedings of the International Conference on the Theory and Applications of Cryptographic Techniques*, vol. 2332 of *Advances in Cryptology - EUROCRYPT 2002*, pp. 83–107, Amsterdam, The Netherlands, April, 2002.

[10] D. He, S. Zeadally, and L. Wu, "Certificateless public auditing scheme for cloud-assisted wireless body area networks," *IEEE Systems Journal*, vol. 12, no. 1, pp. 64–73, 2018.

[11] C. Wang, Y. Han, and F. Li, "A secure mobile agent protocol for m-commerce using self-certified proxy signcryption," in *Proceedings of the 2009 2nd International Symposium on Information Science and Engineering, ISISE 2009*, pp. 376–380, China, December 2009.

[12] H. M. Elkamchouchi and Y. Abouelseoud, "A new proxy identity-based signcryption scheme for partial delegation of signing rights," *Cryptology ePrint Archive*, vol. 2008, p. 41, 2008.

[13] N.-W. Lo and J.-L. Tsai, "A provably secure proxy signcryption scheme using bilinear pairings," *Journal of Applied Mathematics*, vol. 2014, 2014.

[14] Z. Liu, Y. Hu, X. Zhang, and H. Ma, "Certificateless signcryption scheme in the standard model," *Information Sciences*, vol. 180, no. 3, pp. 452–464, 2010.

[15] Q. Yanfeng, T. Chunming, L. Yu, X. Maozhi, and G. Baoan, "Certificateless proxy identity-based signcryption scheme without bilinear pairings," *China Communications*, vol. 10, no. 11, pp. 37–41, 2013.

[16] T. Bhatia and A. K. Verma, "Cryptanalysis and improvement of certificateless proxy signcryption scheme for e-prescription system in mobile cloud computing," *Annals of Telecommunications-Annales des Télécommunications*, vol. 72, no. 9-10, pp. 563–576, 2017.

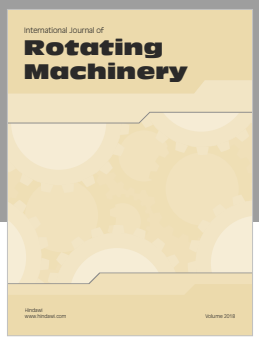
[17] Z. Ullah, I. Ullah, H. Khan, H. Khattak, and S. Ullah, "Secure protocol for mobile agents using proxy signcryption scheme based on hyper elliptic curve," *International Journal of Computer Science and Information Security<*, vol. 14, no. 2, p. 1009, 2016.

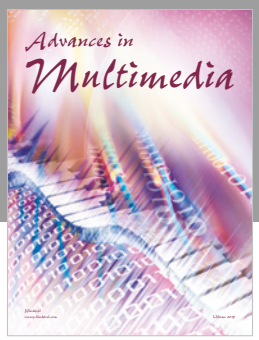
[18] V. Saraswat, R. A. Sahu, and A. K. Awasthi, "A secure anonymous proxy signcryption scheme," *Journal of Mathematical Cryptology*, vol. 11, no. 2, pp. 63–84, 2017.

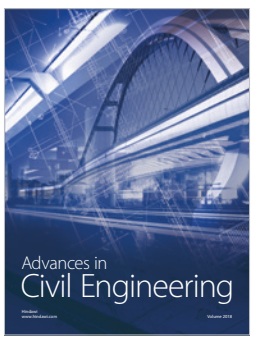
[19] Shamus software ltd., miracl library. http://www.shamus.ie/index.php?page=home, 2016.

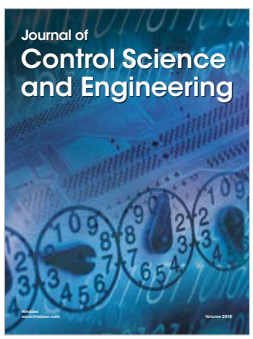
[20] D. He, S. Zeadally, N. Kumar, and W. Wu, "Efficient and Anonymous Mobile User Authentication Protocol Using Self-Certified Public Key Cryptography for Multi-Server Architectures," *IEEE Transactions on Information Forensics and Security*, vol. 11, no. 9, pp. 2052–2064, 2016.

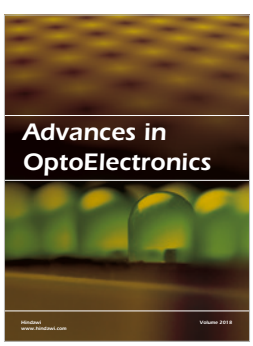
[21] M. Qu, *Sec 2: Recommended elliptic curve domain parameters*, 1999.

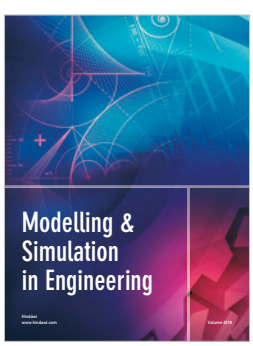


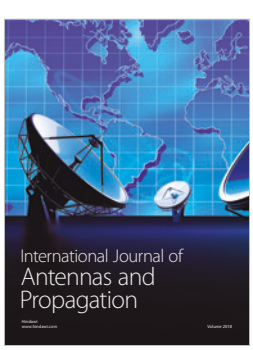


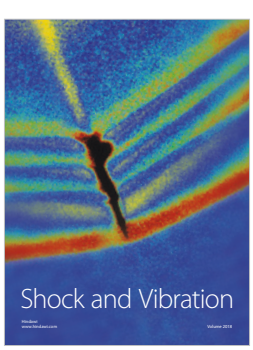


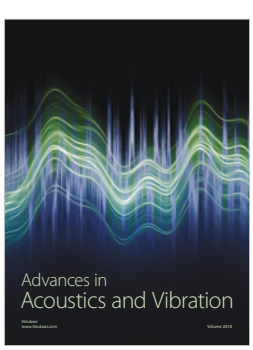












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