Research Article

Traceable Ciphertext-Policy Attribute-Based Encryption with Verifiable Outsourced Decryption in eHealth Cloud

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In cloud-assisted electronic health care (eHealth) systems, a patient can enforce access control on his/her personal health information (PHI) in a cryptographic way by employing ciphertext-policy attribute-based encryption (CP-ABE) mechanism. There are two features worthy of consideration in real eHealth applications. On the one hand, although the outsourced decryption technique can significantly reduce the decryption cost of a physician, the correctness of the returned result should be guaranteed. On the other hand, the malicious physician who leaks the private key intentionally should be caught. Existing systems mostly aim to provide only one of the above properties. In this work, we present a verifiable and traceable CP-ABE scheme (VTCP-ABE) in eHealth cloud, which simultaneously supports the properties of verifiable outsourced decryption and white-box traceability without compromising the physician’s identity privacy. An authorized physician can obtain an ElGamal-type partial decrypted ciphertext (PDC) element of original ciphertext from the eHealth cloud decryption server (CDS) and then verify the correctness of returned PDC. Moreover, the illegal behaviour of malicious physician can be precisely (white-box) traced. We further exploit a delegation method to help the resource-limited physician authorize someone else to interact with the CDS. The formal security proof and extensive simulations illustrate that our VTCP-ABE scheme is secure, efficient, and practical.

1. Introduction

Electronic health care (eHealth) system is regarded as an outstanding approach to provide well health care service through various emerging technologies, including Internet of Things, cloud computing, mobile computing, and wireless sensor networks. In cloud-assisted eHealth systems, an individual patient integrates his/her personal health information (PHI) collected via various wearable and embedded sensors, stores the PHI in the cloud, and receives real-time and high-quality medical treatment. Unfortunately, when the patient enjoys convenient storage services provided by cloud server, the risk of privacy exposure also raises. The sensitive PHI may be exposed to the cloud server which can not be fully trusted. Even worse, the PHI may be widely propagated to unauthorized parties for commerce benefit or other purposes. Thus, the PHI must be encrypted before hosted to the eHealth cloud. Meanwhile, an access policy must be specified to point out who are authorized to access the PHI.

Aiming to realize access control on encrypted message, attribute-based encryption (ABE) [1] was presented to provide an efficient solution to this kind of applications. According to the place where the access policy is embedded, the ABE schemes are divided into two forms, key-policy ABE (KP-ABE) [2] and another type of ABE named ciphertext-policy ABE (CP-ABE) [3]. In the former framework, every user’s key is labeled with an access policy while the ciphertexts are annotated with chosen sets of attributes. On the contrary, the
In this work, we propose a novel verifiable and traceable CP-ABE scheme named VTCP-ABE for eHealth cloud applications. The VTCP-ABE scheme is the first scheme which simultaneously achieves white-box traceability and verifiable outsourced decryption without exposing the physician's identity information. Since we take the 'large universe' scheme [18] as the basis, the attribute universe in our scheme is inherently unbounded. We further extend the VTCP-ABE to support another delegation property. We also provide the formal proof of the selective CPA security, verifiability, and traceability for VTCP-ABE. The comparison and simulation results show that our VTCP-ABE is applicable for practical eHealth cloud applications. In particularly, we make the following contributions:

1. We propose a new VTCP-ABE scheme which simultaneously achieves the properties of verifiable outsourced decryption, white-box traceability, and large universe. An authorized physician can check the correctness of partial decrypted ciphertext (PDC) which is requested from the eHealth CDS. Given a private key, the original owner can be precisely tracked. The attribute universe can be exponentially large and the number of public parameter elements is constant no matter how many attributes are chosen.

2. We present an efficient approach to prevent the CDS from knowing the fixed identification information of physician during offering decryption service. The original ciphertext and the transmission private key will be pre-processed before being sent to the CDS. This method is acceptable since only two additional exponential operations for each decryption request are added.

3. We exploit an additional property of delegation for our VTCP-ABE, with which a resource-constrained physician can delegate someone to obtain a PDC element without compromising the privacy of PHI.

1.1. Related Works. ABE was first introduced in [1]. The first KP-ABE scheme with threshold tree access structures was presented in [2]. The first CP-ABE scheme with the same structures was presented in [3]. Waters [21] presented several CP-ABE schemes to support the access policy defined as Linear Secret Sharing Schemes (LSSS). Yu et al. [22] demonstrated the deployment of ABE technique in cloud computing. In [4], Li et al. presented a personal health record (PHR) secure sharing scheme in cloud computing. Subsequently, various constructions of ABE schemes were presented in [9, 23–29].

Green et al. [13] constructed the first decryption outsourcing ABE, where the most decryption overhead is hosted to a third party. With the returned partial decrypted ciphertext, a user could recover the plaintext message by executing only one exponential operation. Based on the outsourced method [13], Li et al. [7] presented a PHR data sharing scheme for cloud storage applications in the multi-authority settings. In both [7, 13], the correctness of returned PDC is not guaranteed. Lai et al. [14] presented an approach to check whether the partial decrypted ciphertext element (transformed ciphertext element) is correctly calculated. Their technique incurred noticeable overhead in both decryption and encryption. Based on key encapsulation mechanism, Lin
et al. [19] and Qin et al. [15] separately proposed a fascinating method to support verifiable outsourced decryption in ABE. The difference between [19] and [15] is that, in [19], the hash value of a random group element R is set as the symmetric key to encrypt the original data, then R is encrypted by a ABE scheme to obtain a ABE-type ciphertext, which will be used to generate the verification key. In [15], the original data M is encrypted along with a randomly chosen bit string r, while the verification key is set by executing exponential operations in the group by taking the hash values of M and r as exponents.

Liu et al. presented the first adaptively secure and white-box traceable CP-ABE scheme in [16], where any monotonic attribute set adopted in decryption.

Table 1 compares the characteristics between some related works.

### Table 1: Comparison between ours and some related works.

<table>
<thead>
<tr>
<th>Systems</th>
<th>CP/KP</th>
<th>AU</th>
<th>OD</th>
<th>Verifiability</th>
<th>Traceability</th>
<th>Delegation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rouselakis et al. [18]</td>
<td>CP/KP</td>
<td>Large</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Green et al. [13]</td>
<td>CP/KP</td>
<td>Large</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Lai et al. [14]</td>
<td>CP</td>
<td>Small</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Qin et al. [15]</td>
<td>CP</td>
<td>Small</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Liu et al. [16]</td>
<td>CP</td>
<td>Small</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Ning et al. [17]</td>
<td>CP</td>
<td>Large</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Our VTCP-ABE</td>
<td>CP</td>
<td>Large</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

1. AU is the abbreviation of attribute universe.
2. OD is the abbreviation of outsourced decryption.

### 2. Preliminaries

#### 2.1. Bilinear Maps

Denote G and G1 as two multiplicative cyclic groups with prime order p. g is a generator of group G. The bilinear map ε : GxG → G1 has the following properties:

1. Bilinearity: ∀c, η ∈ G and r, v ∈ Zp, ε(c, ηv) = ε(c, η)v.
2. Non-degeneracy: ε(g, g) ≠ 1.
3. Computability: for all c, η ∈ G, ε(c, η) is efficiently computable.

Since that ε(g’, g”)^w = ε(g, g)^w(ε(g”, g’)^w), ε is symmetric.

#### 2.2. Linear Secret Sharing Schemes (LSSS)

**Definition 1.** Linear Secret Sharing Schemes [21, 34]: let P denote a set of attributes, and let p be a chosen prime. Let \( T \in \mathbb{Z}_p \) be a matrix. For all \( i = 1, \ldots, m \), a function \( ρ \) labels the \( i \)-th row of \( T \) with an attribute (i.e., \( ρ \in \mathcal{P}(\{m\} \rightarrow \mathbb{P}) \)). A secret sharing scheme Π over the attribute universe \( \mathbb{P} \) is linear if one has the following:

1. The shares for each attribute make a vector over \( \mathbb{Z}_p \).
2. In order to generate the shares of a secret \( s \in \mathbb{Z}_p \), we select the column vector \( \vec{q} = (q_0, q_1, \ldots, q_n)^t \), where \( q_0, \ldots, q_n \) are randomly selected from \( \mathbb{Z}_p \), then \( T\vec{q} \) is the shares of \( s \) according to Π. The share \( (T\vec{q})_i \) belongs to the attribute \( ρ(i) \).

As demonstrated in [34], the linear reconstruction property of LSSS is defined as follows: Suppose \( (T, ρ) \) is the access structure \( \mathcal{T} \) and \( S \) is an authorized set. Let \( I = \{i : ρ(i) ∈ S\} \) be the index set of rows which are linked with the attributes in \( S \). There exist constants \( \psi_i \in \mathbb{Z}_p \) which satisfy that if \( \{λ_i = (T\vec{q})_i\} \) are valid, then we have \( \sum_{i∈I} \psi_iλ_i = s \).

#### 2.3. \( ϕ \)-Type Assumption

The security of VTCP-ABE is reduced to a \( ϕ \)-type assumption [18].

Suppose \( G \) is a cyclic group and prime \( p \) is the group order. Randomly pick \( g \in G \) and choose \( i, s, v_1, v_2, \ldots, v_ϕ \in \mathbb{Z}_p \). An adversary \( \mathcal{A} \) is given the group description \( (p, G, G_1, ε) \) and \( \Xi \) including all of the following terms:

\[
\Xi = g, g^i, g^{v_i}, g^{v_{i,j}}, g^{v_{i,j}^2}, \forall (i, j) [\varphi, \varphi] \\
g^{v_{i,j}^2} \forall (i, j, j') [2\varphi, \varphi] \text{ with } i ≠ j + 1 \\
g^{v_{i,j}^2} \forall (i, j, j') [2\varphi, \varphi] \text{ with } j ≠ j' \\
g^{v_{i,j}^2} \forall (i, j, j') [\varphi, \varphi, \varphi] \text{ with } j ≠ j'
\]

It must be hard for \( \mathcal{A} \) to distinguish the element \( ε(g, g)^{v_{i,j}^2} ∈ G_1 \) from a randomly chosen element \( F ∈ G_1 \).
The advantage of an algorithm $\mathcal{A}$ which solves the above $q$-type problem is

$$\text{Adv}_{\mathcal{A}(\lambda)} = \left| \Pr \left[ \mathcal{A}(\Xi, W = e(g, g)^{\epsilon+1}) = 0 \right] - \Pr \left[ \mathcal{A}(\Xi, W = F) = 0 \right] \right|$$

(1)

**Definition 2.** We claim that the $\varphi$-type assumption holds if the advantage of all polynomial time adversaries is negligible in the above $\varphi$-type game.

2.4. $\vartheta$-Strong Diffie-Hellman Assumption ($\vartheta$-SDH). The $\vartheta$-SDH problem [35, 36]: suppose $G$ is a cyclic group. Let prime $p$ be the group order. $g$ is randomly selected from $G$. Given a $(\vartheta + 1)$-tuple $(g, g^\varphi, g^{\varphi^2}, \ldots, g^{\varphi^\vartheta})$, output a pair $(\vartheta, g^{1/(\vartheta \varphi)^\delta}) \in Z_p \times G$. An algorithm $\mathcal{A}$ has advantage $\epsilon$ in solving $\vartheta$-SDH problem if $\Pr[\mathcal{A}(g, g^\varphi, g^{\varphi^2}, \ldots, g^{\varphi^\vartheta}) = (\vartheta, g^{1/(\vartheta \varphi)^\delta})] \geq \epsilon$, where the randomness of $\vartheta$ is over the random bits consumed by $\mathcal{A}$ and the randomness of $\varphi \in Z_p$.

**Definition 3.** We claim that the $(\vartheta, t, \epsilon)$-SDH assumption holds if the advantage of all $t$-time adversaries is at most $\epsilon$ in solving the above $\vartheta$-SDH problem.

### 3. System Architecture and Security Model

#### 3.1. System Description.

As shown in Figure 1, our VTCP-ABE framework in the eHealth cloud mainly consists of the following components.

- **The authority:** the authority produces the system parameters and generates private keys for the legal physicians depending on their attributes. It is also in charge of tracing the malicious physicians.
- **The patient:** with the help of IOT techniques, the patient integrates and then encrypts his/her PHI under appropriate access policy and further uploads the ciphertext to the eHealth cloud storage server.
- **The eHealth cloud storage server (CSS):** the eHealth CSS provides storage service for the patient. If necessary, the patient can call CSS to delete his/her PHI data.
- **The eHealth cloud decryption server (CDS):** the eHealth CDS provides pre-decryption service of the encrypted PHI and returns the partial decrypted ciphertext to the authorized physician.

The physician: the physician takes responsibility of medical treatment for the patient whose access policy accepts his/her attributes. The physician is also enabled to check the correctness of returned pre-decryption results from the CDS. The malicious physician may leak his private key for economic benefit or some malignant purpose.

We note that the eHealth CSS and CDS are assumed to be semi-trusted as in [22]. That is, the CSS and CDS honestly execute the pre-set algorithms. But they attempt to get useful information of the encrypted PHI as much as possible. In addition, the eHealth CDS may want to obtain the identification information of physician.

As one of the important applications in IOT environments, the eHealth cloud system enables the patient to collect his PHI via wearable devices, physiologic sensor nodes and body area networks, etc. Before uploading the PHI to the cloud server get real-time health care services, the patient can define expressive access policy of his PHI over descriptive attributes by VTCP-ABE. According to the assigned attributes, the individual physicians have differential flexible access rights. They can provide various (free or paid) health care services by smart devices on condition that their attributes match the access policy of patient's PHI. Our VTCP-ABE also offers the traceability to prevent the key abuse problem and the verifiable outsourced decryption technique to offload most decryption cost to the cloud server and guarantee the returned results.

#### 3.2. Definition of VTCP-ABE.

Our VTCP-ABE is comprised by the following seven algorithms.

- **Setup** $(\kappa, U) \rightarrow (PK, MSK)$: this algorithm takes in a security parameter $\kappa$ and the system attribute universe $U$. It then outputs the system public parameters $PK$ and the master secret key $MSK$. Besides, it initializes an identity table $I^T = \emptyset$.

- **Encrypt** $(M, PK, T) \rightarrow (CT, VK)$: this algorithm takes in a message $M$, $PK$, and an access structure $T$. It then outputs a ciphertext $CT$ and a verification key $VK$.

- **KeyGen** $(PK, MSK, id, S) \rightarrow (TK, DK)$. This algorithm takes in $PK$, $MSK$, an identity information $id$ and an attribute set $S$. It then outputs a transmission private key $TK$ and a user decryption key $DK$.

- **Pre-Process** $(PK, CT, TK) \rightarrow (PCT, PTK)$. This algorithm takes in $CT$ and $TK$. It then outputs a pre-processed ciphertext $PCT$ and a pre-processed private key $PTK$.

- **Pre-Decrypt** $(PCT, PTK) \rightarrow (PDC)$. This algorithm takes in $PCT$ and $PTK$. If $S$ matches $T$, the algorithm outputs a partial decrypted ciphertext $PDC$. Otherwise, it outputs $\bot$.

- **Decrypt** $(PDC, DK, VK) \rightarrow (M)$: This algorithm takes in $PDC$, $DK$, and $VK$. If $PDC$ is not valid, it outputs $\bot$. Otherwise, it outputs a message $M$.

- **Trace** $(IT, PK, TK, DK) \rightarrow id$ or $\tau$. This algorithm takes in $IT$, $PK$, $TK$, and $DK$. It first verifies whether $TK$ and $DK$ are well-formed. If so, this algorithm outputs the $id$ annotated with $TK$ and $DK$. Otherwise, it outputs $\tau$ implying that $TK$ and $DK$ are not required to be traced. If $TK$ and $DK$ can pass
a "key sanity check" which means they can be used in the normal decryption phase, they are called well-formed [16].

3.3. CPA Security Model. Similar to [17,18], the definition of selective security model of VTCP-ABE against chosen plaintext attack (CPA) is given as follows:

**Init.** The adversary \( \mathcal{A} \) gives the simulator \( \mathcal{S} \) the challenge access policy \( T^* \).

**Setup.** \( \mathcal{S} \) runs Setup to produce \((PK, MSK)\) and passes \( PK \) to \( \mathcal{A} \).

**Phase 1.** \( \mathcal{A} \) can ask \( \mathcal{S} \) to produce the private keys for \((id_1, S_1), (id_2, S_2) , \ldots , (id_{Q_1}, S_{Q_1})\). For each \((id_i, S_i)\), \( \mathcal{S} \) returns by the corresponding private key pairs \((TK_i, DK_i)\). Note that, for each \(i \in [Q_1], S_i \) can not match \( T^* \).

**Challenge Phase.** \( \mathcal{A} \) submits two messages \( M_0 \) and \( M_1 \) of equal length. \( \mathcal{S} \) encrypts \( M_\mu \) under \( T^* \) to obtain \( CT^* \) and \( VK^* \), where \( \mu \) is randomly chosen from \([0,1]\). It then gives \( CT^* \) and \( VK^* \) to \( \mathcal{A} \).

**Phase 2.** As in Phase 1, \( \mathcal{S} \) is asked to produce the private keys of \((id_{Q_1+1}, S_{Q_1+1}) , \ldots , (id_{Q_2}, S_{Q_2})\).

**Guess.** \( \mathcal{A} \) guesses \( \mu^* \) for \( \mu \). \( \mathcal{A} \)'s advantage is defined as \( \Pr[\mu^* = \mu] - 1/2 \).

**Definition 4.** We claim that a VTCP-ABE scheme is selectively CPA secure if the advantage is negligible for all PPT adversaries in the above selective security game.

3.4. Security Game for Verifiability. Based on the replayable chosen ciphertext attack (RCCA) security model [13,15], we briefly introduce the verifiability game as follows.

**Setup.** The challenger \( \mathcal{S} \) generates \((PK, MSK)\) and sends \( PK \) to the attacker \( \mathcal{A} \).

**Phase 1.** \( \mathcal{A} \) queries the results from the Create, Corrupt, and Decrypt oracles as in [15].

**Challenge Phase.** The attacker \( \mathcal{A} \) submits an access policy \( T^* \) and a message \( M^* \). \( \mathcal{S} \) encrypts \( M^* \) under \( T^* \) to obtain \( (CT^*, VK^*) \) and sends them to \( \mathcal{A} \).

**Phase 2.** \( \mathcal{A} \) repeats the key queries as in Phase 1.

**Output.** \( \mathcal{A} \) gives \( \mathcal{B} \) \( PDC^* \) and an attribute set \( S^* \) which satisfies \( T^* \).

The attacker \( \mathcal{A} \) wins the above game if \( \text{Decrypt}(PDC^*, DK^*, VK^*) \notin \{M, \bot\} \). \( \mathcal{A} \)'s advantage in this game is defined as \( \text{ADV}_{\text{VTCP-ABE}}^{\mathcal{A}} \).

**Definition 5.** We claim that a VTCP-ABE scheme is verifiable if \( \text{ADV}_{\text{VTCP-ABE}}^{\mathcal{A}} \) is negligible for all PPT attackers in the above game.

3.5. Security Game for Traceability. The traceability game of our VTCP-ABE is defined as follows.

**Setup.** The challenger \( \mathcal{S} \) generates \((PK, MSK)\) and sends \( PK \) to the attacker \( \mathcal{A} \). It keeps \( MSK \) as a secret key.

**Key Query.** \( \mathcal{A} \) submits the tuples \((id_1, S_1), (id_2, S_2) , \ldots , (id_{q^*}, S_{q^*})\) to \( \mathcal{S} \), where \( q \) refers to the query number that \( \mathcal{A} \) can make.

**Key Forgery.** \( \mathcal{A} \) outputs \( DK^* \) and \( TK^* \). \( \mathcal{A} \) wins if \( \text{Trace}(IT, PK, DK^*, TK^*) \neq T \) and \( \text{Trace}(IT, PK, DK^*, TK^*) \neq [id_1, id_2, \ldots , id_{q^*}] \). \( \mathcal{A} \)'s advantage is defined as \( \Pr[\text{Trace}(IT, PK, DK^*, TK^*) \neq T] \cup [id_1, id_2, \ldots , id_{q^*}] \).

**Definition 6.** We claim that a VTCP-ABE scheme is fully traceable if the advantage is negligible for all PPT attackers in the above game.

4. The Proposed VTCP-ABE

In this section, we first briefly introduce the techniques of constructing a verifiable and traceable CP-ABE scheme and then give the details of VTCP-ABE construction.

4.1. Technical Overview. To achieve the traceability in [17], each private key is associated with a unique fixed number \( \delta \) so that the key owner cannot re-randomize his own private key to get a completely new key. In the verifiable CP-ABE scheme with outsourced decryption [15], the private key is composed of a transmission key and a user decryption key. The transmission key is sent to a third party to get the partial decryption result and the user decryption key is used to decrypt the partial decryption result and check its correctness.

Our goal is to achieve the efficient user decryption and traceability without compromising the security and privacy. However, if we combine the traceable CP-ABE [17] and the verifiable outsourced decryption approach [15] in a naive way, the fixed identifier number \( \delta \) will be exposed to the eHealth CDS. Even worse, the CDS may use \( \delta \) and the transmission private key to fabricate a key which could pass the check in the traceable algorithm of [17]. That is, a legal physician may be framed to be malicious and further revoked from the system. To prevent the CDS from knowing \( \delta \), we process the transmission private key and original ciphertext before submitting them to the eHealth CDS. Meanwhile, we add the user decryption key as input of the traceable algorithm. Finally, we add the property of verifiable outsourced decryption into the traceable CP-ABE scheme [17] at a very low cost on the physician side (one additional element in private key, two additional exponential operations in pre-processing).

4.2. Detailed Construction. We now give the detailed construction of the VTCP-ABE.

**Setup.** Given a group description \( G = (p, G, G_1, e) \), where prime order \( p \) is the order of groups \((G, G_1)\) and \( e \) denotes a map \( e : G \times G \rightarrow G_1 \). The system attribute universe is set as \( U = Z_p \). Then randomly pick \( g, u, h, w, v \in G \) and \( a, a \in Z_p \).

Select two collision-resistant hash functions \( HA_1 : G_1 \rightarrow \{0,1\}^{\ell_{HA_1}} \) and \( HA_2 : \{0,1\}^* \rightarrow \{0,1\}^{\ell_{HA_2}} \). \( SE = (SE\text{-Keygen}, SE\text{-Encrypt}, SE\text{-Decrypt}) \) refers to a one-time symmetric encryption scheme and the key space is defined as \( \{0,1\}^{\ell_{SE}} \). Select \( HA_3 : G_1 \rightarrow \{0,1\}^{\ell_{HA_3}} \) from \( \mathcal{R} \), which denotes a party of pairwise independent hash functions.

It sets \( (G, g, u, h, w, v, e(g, g)^a, g^a, SE, HA_1, HA_2, HA_3) \) as PK and \((a, a)\) as MSK. It also initializes \( IT = \varnothing \).

**Encrypt.** Given the PHI data \( M \in N \) and a LSSS policy \( T = (T, \rho) \in (Z_p)^{m\times n}, \rho : [m] \rightarrow Z_p \), the encryption algorithm acts as follows.

Randomly select \( \chi \in G_1 \) and \( \varrho = (s,q_2,\ldots, q_n)^\top \in Z_p^{nx1} \). Calculate \( \overrightarrow{\lambda} = T \cdot \overrightarrow{\varrho} = (\lambda_1, \lambda_2, \ldots, \lambda_n)^\top \). Choose \( t_1, t_2, \ldots , t_m \) randomly from \( Z_p \) and compute...
For each \( i \in [m] \), compute \( C_{1,i} = w^{\alpha_i}, C_{2,i} = (w^{\beta_i})^h \) and \( C_{3,i} = g^{\gamma_i} \).

The ciphertext of \( \chi \) is \( CT' = (T, C_{1,1}, C_{1,2}, |C_{1,1}|, C_{1,2}), C_{2,1} \) is loaded to the eHealth CSS, which will be sent to the eHealth CDS.

After that, this algorithm sets \( TAG_1 = HA_1(\chi) \), and computes a symmetric key \( SEK = HA_3(\chi) \). Then it calls \( SE-Encrypt(\mathcal{M}, SEK) \) and the verification key \( VK = HA_3(TAG_1 \parallel CT_M) \).

Finally, the ciphertext of PHI data \( CT = (CT', CT_M) \) is uploaded to the eHealth CSS as well as VK.

**KeyGen.** Given a tuple \((id, S) = \{AT_1, AT_2, \ldots, AT_k\} \subseteq Z_p\), this algorithm randomly selects \( b, \delta, \beta, \beta_1, \ldots, \beta_k \in Z_p \) and then calculates

\[
KK = g^{(a+b)\delta}w^\beta, \quad KK_1 = \delta,
\]

where \( a = \sum_{i \in I} (\theta(i) - \delta) \).

Finally, it outputs \( PDC = C' \).

**Decrypt.** This algorithm first computes \( \chi = C/(C')^b \). Then it calculates \( TAG_1 = HA_1(\chi) \). If \( HA_2(TAG_1 || CT_M) \neq VK \), it aborts immediately. Otherwise, it calculates \( SEK = HA_3(\chi) \) and recovers \( M = SE-Decrypt(CT_M, SEK) \).

**Trace.** This algorithm first verifies whether \( TK \) and \( DK \) are well-formed by the following checks:

1. TK is expressed as \((S, KK, KK_1, L_1, L_2, \{KK_{r,1}, KK_{r,2}\}_{r \in [k]}), \) where \( KK_1 \in Z_p \) and \( KK, L_1, L_2, KK_{r,1}, KK_{r,2} \in \mathbb{G} \).
2. \( DK = b \in Z_p \).
3. e(g, L_2) = e(g^b, L_1).
4. \( e(KK, g^a \cdot g^{KK_1}) = e(g^b, g^{\alpha_b}e(L_1^{KK_1}L_2, w) \).
5. \( \exists \tau \in [k], \) s.t. \( e(KK_{r,1}, g)e(L_1^{KK_{r,1}}L_2, \nu) = e(KK_{r,1}, \nu)e(KK_{r,1}, L_1^{KK_{r,1}}) \).

If TK and DK fail to pass the above five checks, it outputs \( \top \). Otherwise, it searches \( KK_1 \) in \( IT \): if \( KK_1 \) exists, it outputs the corresponding \( id \). If \( KK_1 \) does not exist, it aborts.

For each \( \tau \in [k] \), it computes \( KK_{r,1} = g^{b_\tau} \) and \( KK_{r,2} = (a^\tau A_T)h^b \cdot y^{-\delta \beta} \).

Finally, it outputs the private key for \((id, S) \) as \( TK = (S, KK, KK_1, L_1, L_2, \{KK_{r,1}, KK_{r,2}\}_{r \in [k]}), DK = b \). Simultaneously, the tuple \((id, \delta) \) is added to \( IT \).

**Pre-Process.** The physician can request the PHI ciphertext \( CT = (CT', CT_M) \) and \( VK \) from the eHealth CSS, which will respond by the elements \( C_{1,1}, C_{1,2}, CT_M \) and \( VK \) while the other elements will be sent to the eHealth CDS.

Before calling the pre-decryption service, he/she processes the \( C_{1,2}, C_{1,1}, \) and TK by calculating \( C_3 = C_1^{KK_{r,2}}c_2 = g^{(a+\delta)\beta} \) and \( L_3 = L_1^{KK_{r,1}}L_2 = g^{\alpha_b} \).

Then \( PCT' = C_3 \) and \( PTK = (KK, L_3, \{KK_{r,1}, KK_{r,2}\}_{r \in [k]}) \) are sent to the eHealth CDS.

**Pre-Decrypt.** Once receiving \( PCT' \) and \( PTK \), this algorithm works as follows.

If \( S \) does not match \( T \), this algorithm aborts. Otherwise, it sets \( T_i = \{i : \rho(i) \in S\} \) and calculates constants \( \nu_i \in Z_p \) such that \( \sum_{i \in T_i} \psi_i = (1, 0, \ldots, 0) \), where \( T_i \) refers to the \( i \)-th row of \( T \). Then it calculates

\[
L_1 = g^{\delta_1}, \quad L_2 = g^{\delta_2}.
\]

**5. Security Proof**

**5.1. CPA Security.** For simplicity, the security of the presented VTSCP-ABE scheme is reduced to that of the traceable scheme [17] which is proved under the \( \varphi \)-type assumption. We let \( \sum_{\text{TCP-ABE}} \) and \( \sum_{\text{VTSCP-ABE}} \) denote the traceable scheme [17] and our VTSCP-ABE scheme, respectively.

**Theorem 7.** Suppose that \( \sum_{\text{TCP-ABE}} \) is selectively secure, the one-time symmetric encryption scheme SE is semantically secure, \( HA_3 \) is chosen from a party of pairwise independent hash functions, and the parameters satisfy \( 0 < \epsilon_{SE} \leq (\log |\mathcal{X}| - \epsilon_{HA}) - 2 \log(1/e_{HA}) \). Then, the proposed \( \sum_{\text{VTSCP-ABE}} \) is selectively secure.

**Proof.** Similar to the proof in [15], we define a series of hybrid arguments of games as in [37].

**Game_0.** Identical to the original security game as defined in Section 3.3.
Game\textsubscript{1}. Identical to Game\textsubscript{0}, except that TAG\textsuperscript{*}\textsubscript{1} and SEK\textsuperscript{*} are computed by selecting another random key R\textsuperscript{*} rather than \(\chi\) in CT\textsubscript{T}.

Game\textsubscript{2}. Identical to Game\textsubscript{1}, except that we replace SEK\textsuperscript{*} by a randomly selected string SEK\textsubscript{2} \in \{0, 1\}\textsubscript{SE}.

Let SPB\textsubscript{1} be the success probability of the attacker in Game\textsubscript{2}.

Lemma 8. If \(\sum_{\text{TCP-ABE}}\) is selectively secure, then the attacker can not distinguish Game\textsubscript{0} from Game\textsubscript{1} with a non-negligible advantage.

Proof. Suppose that an attacker \(\mathcal{A}\) can distinguish Game\textsubscript{0} from Game\textsubscript{1}, then we can build a PPT algorithm \(\mathcal{B}\) to break \(\sum_{\text{TCP-ABE}}\).

Setup. Based on \(\mathcal{T}\), \(\sum_{\text{TCP-ABE}}\) gives \(\mathcal{B}\) the parameter \(PK_{\text{TCP-ABE}} = (G, g, u, h, w, v, e(g, g)^{\alpha}, g^\beta)\) as in [17]. After that, \(\mathcal{B}\) chooses SE\textsuperscript{*} and sets \(H_{\text{A}1}, H_{\text{A}2}\) and \(H_{\text{A}1}\) as random oracles. It also sets \(T^*\). Finally, it sends \(PK^* = (PK_{\text{TCP-ABE}} \ast SE^*, H_{\text{A}1}, H_{\text{A}2}, H_{\text{A}3})\) to \(\mathcal{A}\).

Phase 1. To reply the key query of \((id, S)\) from \(\mathcal{A}\), \(\mathcal{B}\) transmits \((id, S)\) to \(\sum_{\text{TCP-ABE}}\) and obtains \(SK_{\text{TCP-ABE}} = (S, KK, KK_1, L_1, L_2, (KK_{1\tau}, KK_{2\tau})\text{\textsubscript{re}}\{[k]\})\), where

\[
\begin{align*}
KK &= g^{\alpha(a+\delta)}w^\delta, \\
KK_1 &= \delta, \\
L_1 &= g^\beta, \\
L_2 &= g^{\beta\delta}.
\end{align*}
\]

\(\forall \tau \in [k]\), \(KK_{1\tau} = g^{\beta\tau}\) and \(KK_{2\tau} = (u^{AT\tau}h)^{\beta\tau}v^{-(a+\delta)\beta}\).

\(\mathcal{B}\) randomly picks \(b \in \mathbb{Z}_p\) and sets

\[
\begin{align*}
KK_1 &= (KK)^{1/b} = g^{\alpha(a+\delta+b)}w^\delta, \\
KK_2 &= \delta, \\
L_1 &= (L_1)^{1/b} = g^\beta, \\
L_2 &= (L_2)^{1/b} = g^{\beta\delta}.
\end{align*}
\]

For each \(\tau \in [k]\), it computes \(KK_{1\tau} = (KK_{1\tau})^{1/b} = g^\beta\), and \(KK_{2\tau} = (KK_{2\tau})^{1/b} = (u^{AT\tau}h)^{\beta\tau}v^{-(a+\delta)\beta}\).

\(\mathcal{B}\) implicitly sets \(\beta = (\beta_1)^{1/b}\) and \(\beta_2 = (\beta_2)^{1/b}\).

Finally, \(\mathcal{B}\) sends \(TK = (S, KK, KK_1, L_1, L_2, [KK_{1\tau}, KK_{2\tau}]\text{\textsubscript{re}}\{[k]\})\) and \(DK = b\) to \(\mathcal{A}\). Simultaneously, it adds \((id, \delta)\) to \(\mathcal{T}'\).

Challenge. \(\mathcal{A}\) submits two equal-length messages \(M_0\) and \(M_1\), and \(\mathcal{B}\) first picks two independent random keys \(\chi\) and \(R\) from \(G_1\). It sends \((M_0\ast = \chi, M_1\ast = R, \mathcal{T}')\) to \(\sum_{\text{TCP-ABE}}\). \(\sum_{\text{TCP-ABE}}\) responds by a challenge ciphertext \(CT_{M_\ast} = (\mathcal{T}', C_1, C_2, [C_{1\tau}, C_{2\tau}]\text{\textsubscript{re}}\{[m]\})\). Then, \(\mathcal{B}\) computes \(SEK^\ast = H_{\text{A}1}(R)\) and \(TAG^\ast_1 = H_{\text{A}1}(R^\ast)\). It randomly picks \(\mu \in \{0, 1\}\) and calculates \(CT_{M_\mu} = \text{SE-Encrypt}(M_\mu, SEK^\ast)\). It also computes \(VK^\ast = TAG^\ast_2 = H_{\text{A}2}(TAG^\ast_1 \parallel CT_{M_\ast})\).

Finally, it sends \(CT^\ast = (CT_{M_\mu}, CT_{M_\mu})\) and \(VK^\ast\) to the attacker.

Note that, if the key encrypted under \(\mathcal{T}'\) in \(CT_{M_\ast}\) is \(R^\ast\), \(CT^\ast\) is regarded as a challenge ciphertext in Game\textsubscript{1}. Otherwise, \(CT^\ast\) can be regarded as a challenge ciphertext in Game\textsubscript{2}.

Phase 2. Similar to Phase 1.

Finally, \(\mathcal{A}\) gives \(\mathcal{B}\) a \(\mu'\), \(\mathcal{B}\) then sends \(\mu'\) to \(\sum_{\text{TCP-ABE}}\). From the above game, we have \(\text{Pr}[\text{SPB}_0] - \text{Pr}[\text{SPB}_1] \leq 2\text{ADV}_{\mathcal{B}} \sum_{\text{TCP-ABE}}\).

Lemma 9. Suppose that \(\mathcal{H}\) is a family of pairwise independent hash functions, then Game\textsubscript{1} can not be distinguished from Game\textsubscript{2} with a non-negligible advantage.

Proof. The key \(R^\ast\) is completely independent of \(PK, CT_{M_\mu}\), and \(HA_{1\ast}\) in both Game\textsubscript{1} and Game\textsubscript{2}. Moreover, the number of possible values of \(TAG^\ast_1 = HA_{1\ast}(R^\ast)\) is at most \(2^{\ell_{HA_{1\ast}}}\).

According to the analysis in [15] and \(0 < \ell_{SE} \leq \log(|\mathcal{H}|) - 2\log(1/e_{HA_{1\ast}})\), the SEK\textsuperscript{*} = \(HA_{1\ast}(R^\ast)\) is \(e_{HA_{1\ast}}\)-statistically indistinguishable from the randomly selected \(R_{SE} \in \{0, 1\}\textsubscript{SE}\). Hence, we have \(\text{Pr}[\text{SPB}_1] - \text{Pr}[\text{SPB}_2] \leq e_{HA_{1\ast}}\).

Lemma 10. Suppose that SE is a semantically secure symmetric encryption scheme, then the attacker can not win Game\textsubscript{2} with a non-negligible advantage.

Proof. In Game\textsubscript{2}, \(R_{SE} \in \{0, 1\}\textsubscript{SE}\) is a truly random symmetric key. An algorithm \(\mathcal{B}\) can be directly constructed from \(\mathcal{A}\) to break the semantic security of SE\textsuperscript{*}. Therefore, we have \(\text{Pr}[\text{SPB}_1] - 1/2 \leq \text{ADV}_{\mathcal{B}}\).

Remark that Game\textsubscript{0} is identical to the selective security game for our proposed VTCP-ABE scheme. The advantage is \(\text{Pr}[\text{SPB}_0] - 1/2\). Thus, the security of our \(\sum_{\text{VTCP-ABE}}\) follows.

5.2. Verifiability

Theorem 11. Suppose that these two hash functions \(HA_{1}\) and \(HA_{2}\) are collision-resistant, our proposed VTCP-ABE scheme is privately verifiable.

Proof. Suppose that an attacker \(\mathcal{A}\) can win the verifiability game, we can employ \(\mathcal{A}\) to build an algorithm \(\mathcal{B}\) to break the collision-resistance of \(HA_{1}\) and \(HA_{2}\).

Given the challenge hash functions \(HA_{1\ast}\) and \(HA_{2\ast}\), \(\mathcal{B}\) processes as follows.

\(\mathcal{B}\) runs Setup to generate PK and MSK, except for \(HA_{1\ast}\) and \(HA_{2\ast}\). To answer the key queries, \(\mathcal{B}\) acts as in Phase 1 and Phase 2.

In the Challenge phase, \(\mathcal{B}\) invokes the Encrypt to obtain the CT\textsuperscript{*}. Then, it computes \(TAG^\ast_1 = HA_{1\ast}(\chi)^{\ast}\) and \(SEK^\ast = HA_{1\ast}(\chi)^{\ast}\). It also calculates \(CT_{M_\ast} = \text{SE-Encrypt}(M_\ast, SEK^\ast)\) and \(VK^\ast = TAG^\ast_2 = HA_{2\ast}(TAG^\ast_1 \parallel CT_{M_\ast})\). It sends \(CT^\ast = (CT_{\chi'}, CT_{M_\ast})\) and \(VK^\ast\) to \(\mathcal{A}\).
outputs an attribute set $S'$ which satisfies $T'$ and a partially decrypted ciphertext $PDC' = C'$ and $CT_{M'}$.

If $\mathcal{A}$ wins the verifiability game, $\mathcal{B}$ will get a message $M \notin [M^*, 1]$. Note that the $\textbf{Decrypt}$ algorithm outputs $\bot$ if $H_{A^*}^2(TAG_1 \parallel CT_{M'}) \neq TAG_1^*$, where $TAG_1 = H_{A^*}^1(\chi)$ and $\chi$ is recovered from $PDC'$ and $CT_{M'}$.

We now analyze the success probability of $\mathcal{A}$ by considering the following cases:

1. $(TAG_1, CT_{M'}) \neq (TAG_1^*, CT_{M'^*})$. If this case happens, $\mathcal{B}$ gets a collision of $H_{A^*}'$ immediately.

2. $(TAG_1, CT_{M'}) = (TAG_1^*, CT_{M'^*})$, but $\chi \neq \chi'$. Note that $H_{A^*}^1(\chi') = TAG_1^* = TAG_1 = H_{A^*}^1(\chi)$. Thus, $\mathcal{B}$ gets a collision of $H_{A^*}'$. $\square$

### 5.3. Traceability

**Theorem 12.** If the $\theta$-SDH assumption holds, then our proposed VTCP-ABE scheme is fully traceable on condition that $q < 8$, where $q$ is the number of key queries made by the attacker $\mathcal{A}$.

**Proof.** We here briefly introduce the traceability proof. Given $(G = (p, G_1, e), g, g^\theta, \ldots, g^{\theta d})$, the simulator $\mathcal{B}$ has to generate a pair $(\delta, g^{\theta d}/\phi) \in \mathbb{Z}_p \times G$ to solve the $\theta$-SDH problem.

**Setup.** Assuming $\theta = q + 1$, $\mathcal{B}$ sets $D_i = g^{\theta i}$ for each $i \in [8]$ and randomly selects $q$ distinct numbers $\delta_1, \ldots, \delta_q$ from $\mathbb{Z}_p^*$. It then sets $f(z) = \prod_{i=1}^{q} (z + \delta_i) = \sum_{i=0}^{q} a_i z^i$, where $a_i$ are the coefficients of $f(z)$. The simulator computes $g \leftarrow \prod_{i=0}^{q} (D_i)^{a_i} = g^{\theta d}$. It then randomly picks $u, h \in G$ and $\alpha, \beta_1, \beta_2 \in \mathbb{Z}_p$. Finally, $\mathcal{B}$ sets $(G, g, u, h, w, g^{\theta 1}, \gamma = g^{\theta 1}, e(g, g)^{\theta 1}, g^{\theta 2}, SE, HA_1, HA_2, HA_3, IT)$ as PK, where $SE, HA_1, HA_2, HA_3$, and $IT$ are set as in the CPA game. It gives $PK \leftarrow \sigma$.

**Key Query.** $\mathcal{B}$ answers the i-th query of $(id_i, S_i)$ as follows.

- $\mathcal{B}$ sets $f_i(z) = f(z)/(z + \delta_i) = \prod_{j=1}^{q} (z + \delta_j) = g^{\theta d}/\phi$ and computes $\mathcal{B}_i \leftarrow \prod_{j=0}^{q} (D_j)^{b_j} = g^{\theta d}/\phi = g^{\theta d}/(g^{\theta d} \phi) = g^{\theta d}/\phi$. Then $\mathcal{B}$ randomly selects $b, \beta_1, \ldots, \beta_k \in \mathbb{Z}_p$ and computes $TK$ by computing:
  
  $KK = (\zeta_1)^{\beta_1} = g^{\theta d \phi} u^{\beta_1}$,
  $KK_1 = \delta_1$,
  $L_1 = g^{\beta_1}$,
  $L_2 = g^{\theta d \phi}$.

  For each $0 \leq \tau \leq [k]$, it computes $KK_{\tau, 1} = g^{\theta \tau}$ and $KK_{\tau, 2} = (u^{\theta \tau \phi})^{\phi} = (u^{\theta (\tau \phi)})^{\phi} = g^{\theta \tau \phi}$.

  It gives $TK$ and $DK = b \leftarrow \sigma$ and add $(id_i, \delta_i)$ to $IT$.

**Key Forgery.** $\mathcal{A}$ submits $TK_{\tau} = (S, KK, KK_1, L_1, L_2, \{KK_{\tau, 1}, KK_{\tau, 2}\} \in [k])$ and $DK = b \leftarrow \mathcal{B}$. $\Psi_{\sigma}$ refers to the event that $\mathcal{A}$ wins, i.e., $TK_{\tau}$ and $DK = b$ are well-formed and $KK_{\tau, 1} \notin \{\delta_1, \delta_2, \ldots, \delta_q\}$.

If $\Psi_{\sigma}$ happens, $\mathcal{B}$ writes $f(z) = f(z) = \phi(z)/(z + KK_1) + \phi_{-1}$ for some polynomial $\phi(z) = \sum_{i=0}^{q} \phi_i z^i$ and some $\phi_{-1} \neq 0 \in \mathbb{Z}_p$. Note that $b$ in $TK_{\tau}$ is unknown to $\mathcal{B}$. $\mathcal{B}$ then computes

$\sigma \leftarrow (KK )^{\phi_{-1}} = g^{\theta d \phi} (\phi_{-1} (z + KK_1))$,
$w_i \leftarrow (\sigma \cdot \prod_{j=0}^{q-1} D_j)^{\phi_{-1}} = g^{\theta d \phi} (\phi_{-1} (z + KK_1))$,

Since $\phi_{-1} (z + KK_1)$ is the solution for the $\theta$-SDH problem.

If $\Psi_{\sigma}$ does not happen, $\mathcal{B}$ randomly picks $(\delta_i, w_i) \in \mathbb{Z}_p \times G$ as the solution.

As analyzed in [17], $\mathcal{B}$'s advantage is non-negligible in solving the $\theta$-SDH problem. $\square$

### 6. Performance Comparison

We here compare the performance of the VTCP-ABE scheme with the TCP-ABE scheme [17] and the VCP-ABE scheme [15] in the setting of key encapsulation, where the PHI data is encrypted by a symmetric encryption key $\chi$ which will be encrypted under an access policy in ABE.

#### 6.1. Numeric Result.

Tables 2 and 3 show the numeric comparison between our scheme and other two schemes [15, 17]. Let $P$, $E$, and $E_1$ be the overhead in executing a bilinear pairing, an exponential operation in $G$ and $G_1$, respectively. $U$ denotes the system attribute universe, $S_C$, $S_A$, and $I$ refer to the set of attributes used in encryption, key generation, and decryption, respectively. Let $H_2$ be the output length of $H_2$.

In Table 2, we calculate the computation cost incurred in the following phases: encryption, key generation, pre-decryption, and user decryption. The user in VCP-ABE and our VTCP-ABE spends constant size computation cost of exponential operation in $G_1$. Note that our VTCP-ABE requires two additional exponential operations in the user side since that the ciphertext and transmission key need to be processed before being transmitted to the eHealth CDS.

In Table 3, the length of system public parameter, private key, and ciphertext is calculated by the number of group elements. The VCP-ABE scheme requires more public parameters which are linear with the scale of system attribute universe due to the fact that all the possible attributes need to be listed during the system initialization phase. Compared with the non-outsourced TCP-ABE scheme, our VTCP-ABE requires an additional element as the user decryption key and an output of $H_2$ as the verification key.

#### 6.2. Implementation.

We implement VCP-ABE scheme [15], TCP-ABE scheme [17], and the proposed VTCP-ABE scheme on a windows 7 platform of an Intel(R) Core(TM) i5-3450 CPU at 3.10 GHz with 8.00 GB Memory. A Type A elliptic curve group is chosen from the JPBC library [38] and the order is a 512-bit prime. We mainly count the computation cost incurred by ABE relevant operations. The computation time of each algorithm is the average of 20 trials.

Figure 2 illustrates the computation cost comparison among VCP-ABE scheme, TCP-ABE scheme, and our proposed VTCP-ABE scheme.
Figure 2(a) shows the computation time in the initialization phase. In the three schemes, the computation cost is mainly incurred by computing the parameters $e(g, g)^a$ and $g^a$.

Figures 2(b) and 2(c) show the computation time in the key generation phase and the encryption phase, respectively. It is observed that the key generation cost and encryption overhead in three schemes are linearly with the number of used attributes. More precisely, TCP-ABE and ours require more computation operation than VCP-ABE since that the combination of parameters $u$ and $h$ is employed to indicate an attribute.

Figure 2(d) shows the computation cost in the pre-process phase of our VTCP-ABE. Two exponential and multiplicative operations in group $G$ are required in computing $C_3$ and $L_3$ no matter how many attributes are involved.

Figure 2(e) illustrates the computation cost comparison in the user decryption phase among three schemes. We can find that the user decryption cost in TCP-ABE scheme increases with the number of attributes. Thanks to the efficient outsourced decryption approach, the final decryption costs on the user side in VCP-ABE scheme and ours are significantly lower than that in TCP-ABE and independent of the attribute number.

Figure 2(f) gives the computation cost comparison in tracing the malicious users between TCP-ABE and ours. We can observe that the computation cost in both scheme grows with the number of attributes and our scheme only requires one additional exponential operation in group $G_1$.

### 7. Delegate Extension

If a physician is in trouble to connect to the eHealth CSS and CDS, he/she can delegate someone to download the PHI ciphertext from the CSS and request the partial decrypted ciphertext from the CDS. However, the access privilege of delegated user has to be restricted. Inspired by [20, 39, 40], we employ a verifiable random function to limit the access of delegated users to maximum $\xi$ times and propose a verifiable and traceable CP-ABE scheme with key delegation (VTCDP-ABE).

**Setup.** Besides generating $PK$ and $MSK$ as in VTCP-ABE, this algorithm calculates $\Omega = e(g, g)$ and chooses a hash function $HA_\xi : \{0, 1\}^* \rightarrow Z_p$. The public parameter is $PK_D = (PK, \Omega, HA_\xi)$.

**Encrypt.** $KeyGen$, **Pre-Process**, **Pre-Decrypt**, and **Trace** algorithms are as well as that in VTCP-ABE.

**Delegate KeyGen.** Given a transmission key $TK = (S, KK, KK_1, L_1, L_2, \{KK_{\tau,1}, KK_{\tau,2}\}_{\tau \in [k]}$) of an id $id$ for a set $S$, an identity information $id_\xi$ and a set $S_D = \{AT_1, AT_2, \ldots, AT_k\} \subseteq S$. This algorithm generates a delegated transmission key $TK_D$ as follows.

Randomly select $d \in Z_p$ and compute $\Gamma_{pse,1} = \Omega^{1/(tdHA_{\xi}(pse))}$, $\Gamma_{pse,2} = g^{\Omega^{1/(tdHA_{\xi}(pse))}}$ and $\Gamma_{pse,3} = g^d$, where $pse$ refers to the unique and random pseudonym of a delegated user. Set $\xi$ as the maximum number of pre-decryption request that a delegated user can make.

Then compute:

- $KK_{pse} = KK^{1/id} = g^{\Omega^{1/d(\Omega HA_{\xi}(pse))}w^{\beta/id}}$,
- $KK_{pse,1} = KK_1 = \delta$,
- $L_{pse,1} = (L_1)^{1/id} = g^{\beta/id}$,
- $L_{pse,2} = (L_2)^{1/id} = g^{\gamma/id}$.

For each $\tau \in [k]$, compute $KK_{pse,\tau,1} = (KK_{\tau,1})^{1/id} = g^{\beta/\tau id}$ and $KK_{pse,\tau,2} = (KK_{\tau,2})^{1/id} = (u^a \gamma)^{\beta/\tau id}$. The $\xi$-times delegated transmission key is set as

$$TK_D = (\xi, pse, S_D, \Gamma_{pse,1}, \Gamma_{pse,2}, \Gamma_{pse,3}, KK_{pse}, KK_{pse,1}, \ldots, KK_{pse,\tau,2})_{\tau \in [k]}.$$  

**Delegate Pre-Process.** The same as Pre-Process, the delegated user requests $CT = (CT_1, CT_2, CT_3)$ from eHealth CSS and computes $C_{pse,3} = c^{KK_{pse,1}}C_2 = g^{(a+\beta)d}$ and $L_{pse,3} = (L_{pse,1})^{KK_{pse,1}}L_{pse,2} = g^{(a+\beta)d/\tau id}$. The delegated user then sends $PCT_D$ and $PTK_D$ to the eHealth CDS, where

$$PCT_D = (\xi, pse, S_D, \Gamma_{pse,1}, \Gamma_{pse,2}, \Gamma_{pse,3}, KK_{pse}, L_{pse,3},$$

$$\{KK_{pse,\tau,1}, KK_{pse,\tau,2}\}_{\tau \in [k]}).$$

$$PTK_D = (\xi, pse, S_D, \Gamma_{pse,1}, \Gamma_{pse,2}, \Gamma_{pse,3}, KK_{pse}, L_{pse,3},$$

$$\{KK_{pse,\tau,1}, KK_{pse,\tau,2}\}_{\tau \in [k]}).$$
Figure 2: Comparisons of computation cost.
Delegate Pre-Decrypt. The eHealth CDS first initializes a counter $c_{ou} = 0$ and a set $S_{psc} = \{\Gamma_{psc,1}\}$ for each delegated user and stores the tuple $(c_{ou}, S_{psc})$ in a delegation list DL. Once receiving the Pre-Decrypt request from a delegated user, the CDS responds by the following way.

If $S$ does not match $T$, it outputs $\bot$.

Otherwise, it searches $(c_{ou}, S_{psc})$ in DL related to $PTK_D$ and checks

1. $e(g^{H/4},\Gamma_{psc,1}) = \Omega$ and $\Gamma_{psc,2} = e(g, \Gamma_{psc,2});$
2. $c_{ou} + 1 < \xi$;
3. $\Gamma_{psc,1} \in S_{psc}$. If the above three conditions do not hold, it aborts.

Otherwise, it updates $c_{ou} \leftarrow c_{ou} + 1$ and computes the partial decryption ciphertext as

$$C_D' = \prod_{i=1}^{\xi} \left( e(K_{psc,1}, \Gamma_{psc,1}) e(K_{psc,1}, C_L) e(K_{psc,1}, C_L) \right)^{\frac{1}{\alpha^i/bd}} = e(g, g)^{\alpha^i/bd}$$

Finally, the CDS responds the delegated user by $PDC_D = C_{D'}$. Then the delegated user gives $PDC_D$ and $CT_M$ to the physician.

Decrypt. If the physician interacts with the CSS and CDS directly, this algorithm acts exactly as in the Decrypt algorithm of VTCP-ABE. If the physician asks a delegated user to get the ciphertext and request the outsourced decryption service, $\chi$ is recovered by $\chi = C/(C_D)^{\alpha^i/bd}$. The verification and PHI decryption operations are identical to that of VTCP-ABE.

Since that the $DK$ of physician and $d$ are kept secretly, the delegated user can not obtain any content of the PHI ciphertext except a partial decrypted ciphertext.

8. Conclusion

In this paper, we have constructed a verifiable and traceable CP-ABE (VTCP-ABE) scheme for eHealth cloud applications, which also achieves the properties of large universe and delegation. With VTCP-ABE, the patient can enforce fine-grained access control over his/her PHI in a cryptographical way. Before submitting the encrypted PHI to the eHealth cloud decryption server, a pre-process on the ciphertext and transmission key is employed to preserve the identity privacy of the physician. The correctness of returned ciphertext can be efficiently verified. Moreover, the malicious physician who leaks the private key can be precisely tracked. Besides, we extend the proposed VTCP-ABE to support the delegation property, with which a resource-limited physician can authorize someone else to obtain a partial decrypted ciphertext without exposing the PHI content. The security of VTCP-ABE is proved in the selective model. The extensive experiments illustrate that our VTCP-ABE scheme efficiently achieves verifiability, traceability, and large attribute universe.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[10] K. Xue, Y. Xue, J. Hong et al., ”RAAC: Robust and Auditable Access Control with Multiple Attribute Authorities for Public