General Certificateless Encryption and Timed-Release Encryption

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Abstract. While recent timed-release encryption (TRE) schemes are implicitly supported by a certificateless encryption (CLE) mechanism, the security models of CLE and TRE differ and there is no generic transformation from a CLE to a TRE. This paper gives a generalized model for CLE that fulfills the requirements of TRE. This model is secure against adversaries with adaptive trapdoor extraction capabilities for arbitrary identifiers, decryption capabilities for arbitrary public keys, and partial decryption capabilities. It also supports hierarchical identifiers. We propose a concrete scheme under our generalized model and prove it secure without random oracles, yielding the first strongly-secure SMCLE and the first TRE in the standard model. In addition, our technique of partial decryption is different from the previous approach.

Key words: security-mediated certificateless encryption, timed-release

1 Introduction

In identity-based encryption (IBE) (e.g. [6, 12, 22, 23, 33]), a public key can be derived from any arbitrary string viewed an identifier (ID). IBE uses a trusted authority, called a key generation center (KGC), to generate ID-based private keys on demand. Since the birth of practical IBE constructions, this idea has been used to achieve other security goals, including certificateless encryption (CLE) [2, 3, 15, 17, 19, 20, 30, 32] and timed-release encryption (TRE) [5, 9–11, 13, 21, 24, 26]. Our main result provides a transformation from a generalized CLE to a TRE.

CLE is intermediate between IBE and traditional public key encryption (PKE). Traditional PKE requires a certification infrastructure but allows users to create their own public/private key pairs so that their private keys are truly private. Conversely, IBE avoids the need for certificates at the expense of adding a KGC that generates the private keys which means the KGC has the capability

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to decrypt all messages. CLE combines the advantages of both: no certificates are needed and messages can only be decrypted by the recipient. Generally, CLE is constructed by combining IBE and PKE. The existence of the PKE component means that the KGC cannot decrypt messages. Instantaneous revocation is difficult for typical CLE schemes. Security-mediated certificateless encryption (SMCLE) addresses this issue. Here we give the first strongly-secure SMCLE in the standard model. Our scheme also supports hierarchical identifiers.

In TRE, the sender encrypts a message under a public key and a time; both the private key and a time-dependent trapdoor are needed for decryption. A time-server is trusted to keep a time-dependent trapdoor confidential until an appointed time. In modern TRE schemes, senders need to retrieve only the system parameters to encrypt. Apart from the obvious application of delayed release of information, TRE supportsmany other applications due to its small trapdoor size and its commitment provision (see [14, 21, 26]). Our general CLE scheme, together with our security-preserving transformation from a general CLE to a TRE, provides the first TRE proven secure in the standard model.

1.1 The difficulty of converting between CLE and TRE

A practical TRE requires system parameters to be small relative to the number of supported time periods. IBE supports an efficent scheme by treating the identities as time periods to provide a time-based unlock mechanism [6, 29]. This approach supports only universal disclosure of encrypted documents since one trapdoor can decrypt all ciphertexts for a specific time; the inherent key-escrow property of IBE prohibits the encryption for a designated receiver.

Since CLE is an "escrow-free version" of IBE, and both TRE and CLE are a kind of double-encryption, it is natural to think CLE is what we are looking for to realize a TRE. While most recent TRE schemes can be viewed as containing an implicit CLE mechanism, a generic conversion is not known. Despite similarities in syntax and functionality, a generic transformation from CLE to TRE is unlikely to be provable secure [9]. Difficulty in reducing the confidentiality of TRE to that of CLE arises when the adversary is a "curious" time-server. In CLE, an identity is associated with only one public key, so a curious KGC is not allowed to replace the public key associated with an identifier arbitrarily (otherwise, decryption is trivial since it holds both parts of secrets). On the other hand, in TRE a time identifier is never bound to any public key, so the public key associated with a time identifier can be replaced. There is no way to simulate this implicit public key replacement when CLE is viewed as a black box.

Other differences between these two notions exist, including a subtle difference in the modelling of an "impatient" recipient. In a secure multi-user system, the security of a user is preserved even if other users are compromised. In CLE, the user secret key together with the trapdoor given by the KGC give the *full* private key. With the assumption that the user secret key will be securely deleted after the combination, most CLE models assume the adversary can get only trapdoors from the KGC and full private keys. For most CLE schemes under this model (e.g. [20]), the user secret key cannot be computed without both the

trapdoor and the full private key. Moreover, while in TRE user secret keys are held by each user, some CLE formulations [3, 27, 32] do not have user secret keys at all, which makes it impossible to reduce the security of TRE to that of CLE.

1.2 Our Contributions

Our generalized model for CLE overcomes the difficulties described in section 1.1 and has sufficient power to fulfill the requirements of TRE. Our model is secure against an adversary with adaptive trapdoor extraction capabilities for arbitrary identifiers (instead of selective identifiers, e.g. [6, 30]), decryption capabilities for arbitrary public keys (as considered in strongly-secure CLE [20]) and partial decryption capabilities (as considered in security-mediated CLE [15]). Our model also supports hierarchical identifiers which have not been considered formally for CLE and TRE. Design choices behind our formulation are justified in section 3.4. as are subtleties involved in building CLE from TRE.

Our model is strong but achievable: section 4 contains a concrete construction under our generalized model. All previous concrete TRE schemes [5, 9–11, 13, 18, 21, 24, 26], and the only concrete SMCLE scheme [15], were proven in the random oracle model. While the generic construction of SMCLE [15] can be instantiated by an IBE and a PKE without random oracles, the resulting scheme is not strongly-secure. Our proposal yields the first strongly-secure SMCLE and the first TRE in the standard model.

This work enriches the study of SMCLE by providing a novel partial decryption technique which is different from that in [15], and enriches TRE by supporting a new business model for the time-server. Finally, hierarchy of identifiers makes decryption of ciphertext for passed periods more manageable.

2 Related Work

2.1 Timed-Release Encryption

Early TRE schemes require interaction with the time-server. Rivest *et al.* [31] require senders to reveal the release-time of the messages in their interactions with the server, so the senders cannot be anonymous to the server. In Di Crescenzo *et al.*'s scheme [18], it is the receiver who interactions with the time-server by invoking a "conditional oblivious transfer protocol" This protocol is computationally intensive, so the time-server is vulnerable to denial-of-service attacks.

Blake and Chan made the first attempt to construct a non-interactive TRE [5]. The formal security model of message confidentiality was later considered independently by Cheon *et al.* [13] and Cathalo, Libert and Quisquater [9]. The former focuses on authenticated TRE. The latter claims to have a stronger model than the implicit non-authenticated version of [13], and formalizes the release-time confidentiality. The recovery of past time-dependent trapdoors from a current trapdoor was studied in [11] and [29], which employs a hash chain and a tree structure [8] respectively. The study of the pre-open capability in TRE was initiated in [26] and improved by [21]. Recently, Chalkias, Hristu-Varsakelis and Stephanides proposed an efficient TRE scheme [10] with random oracles.

2.2 Certificateless Encryption

Al-Riyami and Paterson [2] proposed certificateless encryption in 2003. Extensive surveys of CLE security models and constructions exist [17, 19]. Two types of adversaries are considered in certificateless encryption. A Type-I adversary models coalitions of rogue users without the master secret. Due to the lack of a certificate, the adversary is allowed to replace the public keys of users. A Type-II adversary models a curious KGC who has the master key but cannot replace the public keys of any users. In Al-Riyami and Paterson's security model for the encryption [2], a Type-I adversary can ask for the decryption of a ciphertext under a replaced public key. Schemes secure against such attacks are called "strongly-secure" [20], and the oracle is termed a "strong decryption oracle". A weaker type of adversary, termed Type-I$^-$, can only obtain a correct plaintext if the ciphertext is submitted along with the corresponding user secret key.

The Al-Riyami and Paterson scheme [2] is secure against both Type-I and Type-II adversaries in the random oracle model. It was believed [27, 28, 30] that [28] gives the first CLE in the standard model. However, it is possible to instantiate a prior generic construction in [15] with a PKE and an IBE in the standard model to obtain a secure CLE without random oracles. Both [28] and the instantiation of [15] are only secure against Type-I$^-$ attacks. Based on [22], a selective-ID secure CLE was proposed [30]. This scheme cannot be trivially extended to a TRE since the user's public key is dependent on the identity, but a public key is never coupled with a fixed time-identifier in TRE. Recently, the first strongly-secure CLE in the standard model is proposed [20].

Al-Riyami and Paterson give an extension for hierarchical CLE [2]. However, no security model is given. We are not aware of any literature with formal work on hierarchical CLE, particularly none proven secure in the standard model.

Baek et al. proposed the first CLE that does not use pairings [3]. The CLE proposal [27] uses similar ideas, but their security proof ignores the public key replacement of the target user being attacked. This limitation is removed in Lai and Kou [32]. To replace the pairing, these schemes make part of the user's public key dependent on the identity-specific trapdoor given by the KGC, which means TRE cannot be obtained trivially from these constructions.

Security-mediated certificateless encryption (SMCLE), introduced by Chow, Boyd and González Nieto [15], adds a security-mediator (SEM) who performs partial decryption for the user by request. This idea gives a more general treatment of the decryption queries in the CLE paradigm: the adversary can ask for partial decryption results under either the SEM trapdoor generated by the KGC or the user secret key A concrete construction in the random oracle model and a generic construction in the standard model are proposed in [15]. Prior to our work, no strongly-secure SMCLE existed in the standard model.

3 General Security-Mediated Certificateless Encryption

3.1 Notation

We use an ID-vector $\overset{\#}{ID} = (\mathsf{ID}_1, \mathsf{ID}_2, \cdots, \mathsf{ID}_L)$ to denote a hierarchy of identifiers $(\mathsf{ID}_1, \mathsf{ID}_2, \cdots, \mathsf{ID}_L)$. The length of $\overset{\#}{ID}$ is denoted by $|\overset{\#}{ID}| = L$. Let $\overset{\#}{ID}||\mathsf{ID}_r$ denote the vector $(\mathsf{ID}_1, \mathsf{ID}_2, \cdots, \mathsf{ID}_L, \mathsf{ID}_r)$ of length $|\overset{\#}{ID}| + 1$. We say that $\overset{\#}{ID}$ is a prefix of $\overset{\#}{ID'}$ if $|\overset{\#}{ID}| \leq |\overset{\#}{ID'}|$ and $\mathsf{ID}_i = \mathsf{ID}'_i$ for all $1 \leq i \leq |\overset{\#}{ID}|$. We use $\emptyset$ to denote an empty ID-vector where $|\emptyset| = 0$ and $\emptyset||\mathsf{ID}_r = \mathsf{ID}_r$. Finally, we use the notation $(\{0,1\}^n)^{\leq h}$ to denote the set of vectors of length less than or equal to h, where each component is a n-bit long bit-string.

3.2 Syntax

We propose a new definition of the (security-mediated) certificateless encryption, which also extends the definition of a 1-level SMCLE scheme in [15] to h levels.

Definition 1. *An h-level SMCLE scheme for identifiers of length n is defined by the following sextuple of* PPT *algorithms:*

- Setup *(run by the server) is a probabilistic algorithm which takes a security parameter 1^λ, outputs a master secret key* Msk *(which can also be denoted as $d_\emptyset$), and the global parameters* Pub *(which include $h = h(\lambda)$ and $n = n(\lambda)$ implicitly) We assume all other algorithms take* Pub *implicitly as an input.*
- Extract *(run by the server or any one who holds a trapdoor) is a possibly probabilistic algorithm which takes a trapdoor $d_{\overset{\#}{ID}}$ corresponding to an h-level identifier $\overset{\#}{ID} \in (\{0,1\}^n)^{\leq h}$, and a string $\mathsf{ID}_r \in \{0,1\}^n$, outputs a trapdoor key $d_{\overset{\#}{ID}||\mathsf{ID}_r}$ associated with the ID-vector $\overset{\#}{ID}||\mathsf{ID}_r$. The master secret key* Msk *is a trapdoor corresponding to a 0-level identifier.*
- KGen *(run by a user) is a probabilistic algorithm which generates a public/private key pair $(\mathsf{pk}_u, \mathsf{sk}_u)$.*
- Enc *(run by a sender) is a probabilistic algorithm which takes a message m from some implicit message space, an identifier $\overset{\#}{ID} \in (\{0,1\}^n)^{\leq h}$, and the receiver's public key pk_u as input , returns a ciphertext C.*
- Dec^S *(run by any one who holds the trapdoor, either a SEM in SMCLE or a receiver in CLE) is a possibly probabilistic algorithm which takes a ciphertext C and a trapdoor key $d_{\overset{\#}{ID}}$, returns either a token D which can be seen as a partial decryption, or an invalid flag $\perp$ (which is not in the message space).*
- Dec^U *(run by a receiver) is a possibly probabilistic algorithm which takes the ciphertext C, the receiver's secret key sk_u and a token D as input, returns either the plaintext, an invalid flag $\perp_D$ denoting D is an invalid token, or an invalid flag $\perp_C$ denoting the ciphertext is invalid.*

For correctness, we require that $\mathsf{Dec}^U(C, \mathsf{sk}, \mathsf{Dec}^S(C, \mathsf{Extract}(\mathsf{Msk}, \overset{\#}{ID}))) = m$ *for all $\lambda \in \mathbb{N}$, all* $(\mathsf{Pub}, \mathsf{Msk}) \xleftarrow{\$} \mathsf{Setup}(1^\lambda)$, *all* $(\mathsf{pk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{KGen}$, *all message m, all ID-vector $\overset{\#}{ID}$ in $(\{0,1\}^n)^{\leq h}$ and all* $C \xleftarrow{\$} \mathsf{Enc}(m, \overset{\#}{ID}, \mathsf{pk})$.

3.3 Security

Each adversary has access to the following oracles:

1. An $\mathsf{ExtractO}$ oracle that takes an ID-vector $\vec{ID} \in (\{0,1\}^n)^{\leq h}$ as input and returns its trapdoor $d_{\vec{ID}}$.
2. An UskO oracle that takes a public key pk.as input and returns its corresponding private key sk.
3. A DecO^S oracle that takes a ciphertext C and an ID-vector $\vec{ID}$, and outputs $\mathsf{Dec}^S(C, d_{\vec{ID}})$. Note that C may or may not be encrypted under $\vec{ID}$.
4. A DecO^U oracle that takes a ciphertext C, a public key pk and a token D, and outputs $\mathsf{Dec}^U(C, \mathsf{sk}, D)$ where sk is the secret key that matches pk.
5. A DecO oracle that takes a ciphertext C, an ID-vector $\vec{ID}$, and a public key pk; outputs $\mathsf{Dec}^U(C, \mathsf{sk}, D)$ where sk is the secret key that matches pk, $D = \mathsf{Dec}^S(C, d_{\vec{ID}})$ and C may or may not be encrypted under $\vec{ID}$ and pk.

Following common practice, we consider the two kinds of adversaries.

1. A Type-I adversary that models any coalition of rogue users, and who aims to break the confidentiality of another user's ciphertext.
2. A Type-II adversary that models a curious KGC, who aims to break the confidentiality of a user's ciphertext[3].

We use the common security model in which the adversary plays a two-phased game against a challenger. The game is modeled by the experiment below, $\mathsf{X} \in \{\mathrm{I}, \mathrm{II}\}$ denotes whether an PPT adversary $\mathcal{A} = (\mathcal{A}_{\mathsf{find}}, \mathcal{A}_{\mathsf{guess}})$ is of Type-I or II, and determines the allowed oracle queries $\mathcal{O}$ and the auxiliary data Aux.

Definition 2. Experiment $\mathbf{Exp}_{\mathcal{A}}^{\mathsf{CCA-X}}(\lambda)$

$(\mathsf{Pub}, \mathsf{Msk}) \xleftarrow{\$} \mathsf{Setup}(1^\lambda)$
$(m_0, m_1, \mathsf{pk}^*, \vec{ID}^*, \mathsf{state}) \xleftarrow{\$} \mathcal{A}_{\mathsf{find}}^{\mathcal{O}}(\mathsf{Pub}, \mathsf{Aux})$
$b \xleftarrow{\$} \{0,1\}$, $C^* \xleftarrow{\$} \mathsf{Enc}(m_b, \vec{ID}^*, \mathsf{pk}^*)$
$b' \xleftarrow{\$} \mathcal{A}_{\mathsf{guess}}^{\mathcal{O}}(C^*, \mathsf{state})$
If $(|m_0| \neq |m_1|) \vee (b \neq b')$ *then return 0 else return 1*

$\mathcal{O}$ *is a set of oracles* $\mathsf{ExtractO}(\cdot), \mathsf{UskO}(\cdot), \mathsf{DecO}^S(\cdot,\cdot), \mathsf{DecO}^U(\cdot,\cdot,\cdot), \mathsf{DecO}(\cdot,\cdot,\cdot)$.

Variables marked with * refer to challenges by the adversary. The adversary chooses a public key pk^* and an ID-vector $\vec{ID}^*$ to be challenged with, and the challenger returns a challenge ciphertext C^*. The following two definitions prohibit the adversary from trivially using the oracles to query for the answer to (parts of) the challenge.

[3] A rogue SEM is weaker than a Type-II adversary.

Definition 3. *A hierarchical security-mediated certificateless encryption scheme is (t, q_E, q_D, ϵ) CCA-secure against a Type-I adversary if $|\Pr[\mathbf{Exp}_{\mathcal{A}}^{\mathsf{CCA-I}}(\lambda) = 1] - \frac{1}{2}| \leq \epsilon$ for all t-time adversary $\mathcal{A}$ making at most q_E extraction queries and q_D decryption queries (of any type), subjects to the following constraints:*

1. $\mathsf{Aux} = \emptyset$*, i.e. no auxiliary information is given to the adversary.*
2. *No* $\mathsf{ExtractO}(\overset{\#}{\check{ID}}')$ *query throughout the game, where* $\overset{\#}{\check{ID}}'$ *is a prefix of* $\overset{\#}{\check{ID}}^*$.
3. *No* $\mathsf{UskO}(\mathsf{pk})$ *query throughout the game for any* pk.
4. *No* $\mathsf{DecO}^S(C^*, \overset{\#}{\check{ID}}^*)$ *query throughout the game.*
5. *No* $\mathsf{DecO}(C^*, \overset{\#}{\check{ID}}^*, \mathsf{pk}^*)$ *query throughout the game.*

All public keys in the game are chosen by the adversary. It is natural to assume the adversary knows the corresponding secret keys.

Definition 4. *A hierarchical security-mediated certificateless encryption scheme is (t, q_K, q_D, ϵ) CCA-secure against a Type-II adversary if $|\Pr[\mathbf{Exp}_{\mathcal{A}}^{\mathsf{CCA-II}}(\lambda) = 1] - \frac{1}{2}| \leq \epsilon$ for all t-time adversary $\mathcal{A}$ making at most q_D decryption queries (of any type), subjects to the following conditions:*

1. $\mathsf{Aux} = (\mathsf{Msk}, \{\mathsf{pk}_1^*, \cdots, \mathsf{pk}_{q_K}^*\})$*, i.e. $\mathcal{A}$ is given the master secret and a set of challenge public keys.*
2. $\mathsf{pk}^* \in \{\mathsf{pk}_1^*, \cdots, \mathsf{pk}_{q_K}^*\}$*, i.e. the challenge public key must be among the set given by the challenger.*
3. *No* $\mathsf{UskO}(\mathsf{pk})$ *query throughout the game if* $\mathsf{pk} \notin \{\mathsf{pk}_1^*, \cdots, \mathsf{pk}_{q_K}^*\}$ *or* $\mathsf{pk} = \mathsf{pk}^*$.
4. *No* $\mathsf{DecO}^U(C^*, \mathsf{pk}^*, D)$ *query throughout the game, where D is outputted by the algorithm* $\mathsf{Dec}^S(C^*, d_{\overset{\#}{\check{ID}}^*})$.
5. *No* $\mathsf{DecO}(C^*, \overset{\#}{\check{ID}}^*, \mathsf{pk}^*)$ *query throughout the game.*

Since Msk is given to the adversary, the challenge public key must be in the set given by the challenger.

3.4 Discussions on Our Choices for Definition

This section explains the intuitions behind the choices made in formulating our definition and highlights the relationship between existing definitions and ours.

User key generation. In order to support more general applications like TRE, the interface for the algorithms needs a more general syntax. A subtle change is that our user key generation algorithm KGen only takes the system parameter as input but *not* the identifier. In some CLE schemes [3, 27, 30, 32] the inclusion of the identifier, or the trapdoor for an identifier, is *essential* for the generation of the user public key. For these schemes, KGen can be executed only after $\mathsf{Extract}$, so straightforward adaption results in inefficient TREs in which the size of the user public key grows linearly with the number of supported time periods.

Simplification of Type-I adversary. In existing models for 1-level CLE [2, 20], $\mathsf{ExtractO}$ query of $\overset{\#}{\check{ID}}^*$ is allowed; if such a query is issued, the challenge public key pk^* can no longer be chosen by the adversary. In our discussion, we separate this behavior from the Type-I model and consider this type of adversarial behavior ($\mathsf{ExtractO}(\overset{\#}{\check{ID}}')$ where $\overset{\#}{\check{ID}}'$ is a prefix of $\overset{\#}{\check{ID}}^*$) as a weaker variant of, and hence covered by, a Type-II adversary. It is true that our resulting definition for Type-I adversary is weaker, but the "missing part" is not omitted from the security requirement since CLEs must consider Type-II adversaries; this simplification was justified and adopted in [25, Section 2.3].

Existing models also allow full private key extraction for the public keys prepared by the challenger. In our Type-I game, the challenger does not prepare any public key at all, so UskO query is prohibited. It does not follow that the adversary cannot hold user secret keys. On the contrary, our model offers more: the user secret key can be adversarially generated. The remaining scenario, where the adversary intends to attack a public key given by the challenger, is also a weaker variant of our Type-II model. To conclude, we keep the essence of the existing models, and include UskO to match with TRE.

Strong decryption oracle. In our definition, the decryption oracle works even if the public key is adversarially chosen but the secret key is not supplied. The original definition of CLE [2] does not allow a strong decryption oracle for curious KGC adversary, but it is considered in recent work [20]. Adding the following restriction weakens Definition 4. to correspond to a Type-II$^-$ attack:

5. *(Type-II$^-$) No* $\mathsf{DecO}(C, \overset{\#}{\check{ID}}, \mathsf{pk})$ *query throughout the game for any* C *if* $\mathsf{pk} \notin \{\mathsf{pk}_1^*, \cdots \mathsf{pk}_{q_K}^*\}$*, unless the corresponding secret key* sk *is supplied when the* DecO *query is made.*

The Type-I$^-$ game can be obtained by adding $\mathsf{Aux} = \{\mathsf{pk}_1^*, \cdots \mathsf{pk}_{q_K}^*\}$ and the above restriction to Definition 3.

Implicit public key replacement. In our generalization of CLE, we "remove" (i.e. make implicit) the oracle for replacing the public key corresponding to an identifier. This change may affect the following choices:

1. The adversary's choice of the victim user it wishes to be challenged with,
2. The choice of user in decryption oracle queries.

However, there are other "interfaces" in our model such that the adversary can still make the above choices. Our model still allows the adversary to choose which identifier/public key it wants to attack. For decryption queries, the adversary can just supply different combination of identifier and public key to the DecO^S and DecO^U oracles. In this way, implicit replacement is done. In other words, when compared with the original model [2], the security model is not weakened, but generalized to cover applications of CLE such as TRE.

Reason for "removing" public key request and replacement oracles. In traditional definitions of CLE [2], oracles for retrieving and replacing public key depend upon the fact that an identifier is always bound to a particular user. Replacing a user's public key means changing the public key associated with a certain identifier. In TRE, identifiers correspond to policies governing the decryption, so a single identifier may be "shared" among multiple users. For this reason, our model must be free from the concept of "user = identifier".

Alternative definition of public key replacement. What about allowing a restricted public key replacement, such that a public key associated with an identifier can be replaced by a public key associated with another identifier, but not an arbitrary one supplied by the adversary? This definition still requires an identifier to belong to a single user. Moreover, this definition makes the treatment of a strong decryption oracle complicated: the idea of restricted replacement among a fixed set of public keys does not mesh wll with decrypting under adversarially chosen public keys.

SMCLE is more general than plain CLE. The two separate decryption oracles in the SMCLE model provide a more general notion than CLE:

1. Partial decryption result are not available in the CLE model. Some CLE schemes are not CCA-secure when the adversary has access to a partial decryption oracle [15].
2. Since the decryption oracle is separated in two, the SMCLE model does not have the notion of a "full" private key which is present in previous CLE models (a full private key is a single secret for the complete decryption of the ciphertext). On the ground that separated secrets can always be concatenated into a single full one, this simplification (of private key) has already been adopted in more recent models [25].

Difference with the previous SMCLE definition. Our user decryption oracle DecO^U returns different invalid flags depending on whehter the token from the SEM or the ciphertext is invalid. This distinction is not captured by the original SMCLE model in [15].

User decryption oracle in SMCLE. To exclude trivial attacks, our Type-II adversary model disallows the challenge ciphertext C^* to be decrypted by the decryption oracle under the challenge public key and a token D obtained from the algorithm (not the oracle) $\mathsf{Dec}^S(C^*, \mathsf{ID}^*)$, where ID^* is the challenge identifier. To implement this restriction, our new SMCLE definition checks whether a token D is a *valid* token, corresponding to a ciphertext and an identifier.

While our security definition is tightly coupled with the ability to check the token, we think that it is natural for the user to be able to perform such a test (especially if the user pays for each SEM decryption). Even without an explicit

testing algorithm, it may be possible for the challenger to find a way to do the test for the challenge ciphertext. Our definition is stronger that a definition that prohibits a decryption query for the challenge ciphertext under the challenge public key, no matter what the token is.

Justifications for our definition of hierarchical CLE. In the hierarchical scheme of [2], an entity at level k derives a trapdoor for its children at level $k+1$ using both its trapdoor and its secret key; in our proposed model, a level k entity uses only the trapdoor obtained from its parent at level $k-1$ to derive keys for its children. We do not see any practical reason for requiring the secret key in the trapdoor derivation. Our definition avoids certain complications: for example, in [2], the decryption requires the public keys of all the ancestors.

We do allow the decryption of the ciphertext under $\overset{\#}{\check{I}}\overset{}{D'}$ which is a prefix of $\overset{\#}{\check{I}}\overset{}{D^*}$. This is stronger than the counterpart in some hierarchical IBE models [23].

Summary. Our definition is more general than plain CLE:

Theorem 1 *If there exists a secure* 1*-level SMCLE scheme under Definition 3 and 4, there exists a CLE scheme which is secure under the definition of [2].*

Proof. Our aim is to build a simulator $\mathcal{B}$ which uses of an adversary $\mathcal{A}$ of CLE to break the security of our 1-level SMCLE scheme. The simulator basically forwards everything (the system parameters, the oracle queries and responses, and the guess) back and forth between its own SMCLE challenger and the CLE adversary. Faced with a Type-II adversary of CLE, the simulator acts as a Type-II security of 1-level SMCLE. For a Type-I adversary of CLE, $\mathcal{B}$ flips a fair coin to determine its guess whether $\mathcal{A}$ will issue an $\mathsf{ExtractO}$ query of $\overset{\#}{\check{I}}\overset{}{D^*}$. If it guesses not, $\mathcal{B}$ just plays the Type-I game as usual. If it guesses so, $\mathcal{B}$ will try to use $\mathcal{A}$ to win the Type-II game of SMCLE instead. The $\mathsf{ExtractO}$ query can be answered by $\mathcal{B}$ because it owns Msk now. The reduction tightness is reduced by a factor of 2. This simple trick is also used in [20, Appendix B, Game 4].

We omit the details for most queries, focusing on the important distinctions that involve public key requests and replacement. The simulator must maintain a table to store the binding between an identifier and a public key. Whenever a Type-I adversary issues a public key request query, $\mathcal{B}$ executes $(\mathsf{pk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{KGen}$, stores sk (so $\mathcal{B}$ can reply if $\mathcal{A}$ asks for it), and returns pk. For a Type-II adversary, $\mathcal{B}$ picks a random public key from $\{\mathsf{pk}_1^*, \cdots, \mathsf{pk}_{q_K}^*\}$ in Aux and assigns it as the public key of the queried ID. Whenever $\mathcal{A}$ makes a key replacement query, the simulator updates its own table. For every other requests regarding a particular identifier, the simulator retrieves the corresponding public key from its table and queries its own challenger accordingly. Finally, complete decryption queries of the CLE adversary are answered by combining results from the two partial decryption oracle queries issued by $\mathcal{B}$. □

4 Our Proposed Construction

4.1 Preliminaries

Let $\mathbb{G}$ and $\mathbb{G}_T$ be multiplicative groups of prime order p for which there exists an efficiently computable bilinear map $\hat{e} : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ such that

1. *Bilinearity*: For all $u, v \in \mathbb{G}$ and $r, s \in \mathbb{Z}_p$, $\hat{e}(u^r, v^s) = \hat{e}(u, v)^{rs}$.
2. *Non-degeneracy*: $\hat{e}(u, v) \neq 1_{\mathbb{G}_T}$ for all $u, v \in \mathbb{G} \setminus \{1_{\mathbb{G}}\}$.

The security relies on the intractability of the following problems:

Definition 5. *The* Decision **3**-Party Diffie-Hellman Problem *(3-DDH) in* $\mathbb{G}$ *is to decide if* $T = g^{\beta\gamma\delta}$ *given* $(g, g^\beta, g^\gamma, g^\delta, T) \in \mathbb{G}^5$. *Formally, defining the advantage of a* PPT *algorithm* $\mathcal{D}$, $Adv_{\mathcal{D}}^{3-\mathrm{DDH}}(k)$, *as*

$$\begin{aligned} &| \Pr[1 \xleftarrow{\$} \mathcal{D}(g, g^\beta, g^\gamma, g^\delta, T) | T \leftarrow g^{\beta\gamma\delta} \wedge \beta, \gamma, \delta \xleftarrow{\$} \mathbb{Z}_p^*] \\ &- \Pr[1 \xleftarrow{\$} \mathcal{D}(g, g^\beta, g^\gamma, g^\delta, T) | T \xleftarrow{\$} \mathbb{G} \wedge \beta, \gamma, \delta \xleftarrow{\$} \mathbb{Z}_p^*]|. \end{aligned}$$

We say 3-DDH is intractable if $Adv_{\mathcal{D}}^{3-\mathrm{DDH}}(k)$ *is negligible in* k *for all* PPT $\mathcal{D}$.

Compared with the Bilinear Diffie-Hellman (BDH) problem, the problem instance of 3-DDH is purely in $\mathbb{G}$ while that of BDH contains an element $\hat{t} \in \mathbb{G}_T$. If BDH problem is solvable, one can solve 3-DDH by feeding $(g, g^\beta, g^\gamma, g^\delta, \hat{e}(g, T))$ to a BDH oracle. The above assumption has been employed in [20].

We introduce a variant of the weak Bilinear Diffie-Hellman Inversion (BDHI) assumption [6] below in the favor of 3-DDH. The original h-wBDHI problem in $(\mathbb{G}, \mathbb{G}_T)$ [6] is to decide whether $\hat{t} = \hat{e}(g, g^\gamma)^{\alpha^{h+1}}$. The naming of "inversion" comes from the equivalence to the problem of deciding whether $\hat{t} = \hat{e}(g, g^\gamma)^{1/\alpha}$.

Definition 6. *The* h-Weak Diffie-Hellman Inversion Problem *(h-wDHI) in* $\mathbb{G}$ *is to decide if* $T = g^{\gamma\alpha^{h+1}}$ *given* $(g, g^\gamma, g^\alpha, g^{\alpha^2}, \cdots, g^{\alpha^h}, T) \in \mathbb{G}^{h+3}$. *Formally, defining the advantage of a* PPT *algorithm* $\mathcal{D}$ *as*

$$\begin{aligned} Adv_{\mathcal{D}}^{h-\mathrm{wDHI}}(k) = &| \Pr[1 \xleftarrow{\$} \mathcal{D}(g, g^\gamma, g^\alpha, g^{\alpha^2}, \cdots, g^{\alpha^h}, T) | T \leftarrow g^{\gamma\alpha^{h+1}} \wedge \alpha, \gamma \xleftarrow{\$} \mathbb{Z}_p^*] \\ &- \Pr[1 \xleftarrow{\$} \mathcal{D}(g, g^\gamma, g^\alpha, g^{\alpha^2}, \cdots, g^{\alpha^h}, T) | T \xleftarrow{\$} \mathbb{G} \wedge \alpha, \gamma \xleftarrow{\$} \mathbb{Z}_p^*]|. \end{aligned}$$

We say h-wDHI is intractable if $Adv_{\mathcal{D}}^{h-\mathrm{wDHI}}(k)$ *is negligible in* k *for all* PPT $\mathcal{D}$.

We require a family of collision resistant hash functions $\mathcal{H}$ too.

Definition 7. *A hash function* $H \xleftarrow{\$} \mathcal{H}(k)$ *is* collision resistant *if*

$$Adv_{\mathcal{C}}^{\mathrm{CR}}(k) = \Pr[H(x) = H(y) \wedge x \neq y | (x, y) \xleftarrow{\$} \mathcal{C}(1^k, H) \wedge H \xleftarrow{\$} \mathcal{H}(k)]$$

is negligible as a function of the security parameter k *for all* PPT *algorithms* $\mathcal{C}$.

4.2 Proposed Construction

Our construction is an h-level generalization of the concrete construction for 1-level in [20]. While [20] uses the technique of [7] to achieve strong decryption oracle, we use the same technique for a different purpose, which is a new way (other than the only known way in [15]) to support partial decryption oracle.

$\mathsf{Setup}(1^\lambda, n)$: Let $\mathbb{G}$, $\mathbb{G}_T$ be two multiplicative groups with a bilinear map $\hat{e}$ as defined before. They are of the same order p, which is a prime and $2^\lambda < p < 2^{\lambda+1}$.

- **Encryption key:** choose two generators $g, g_2 \in_R \mathbb{G}$.
- **Master public key:** choose an exponent $\alpha \in_R \mathbb{Z}_p$ and set $g_1 = g^\alpha$.
- **Hash key for identifier-based key derivation:** choose h many $(\ell+1)$-length vectors $\vec{U}_1, \cdots, \vec{U}_h \in_R \mathbb{G}^{\ell+1}$, where each $\vec{U}_j = (u'_j, u_{j,1}, \cdots, u_{j,\ell})$, $1 \leq j \leq h$. ℓ is a tunable parameter which is a factor of n and $1 \leq \ell \leq n$. Each vector $\vec{U}_j$ $(1 \leq j \leq h)$ corresponds to the j-th level of the hierarchy. We use the notation $\vec{ID} = (\mathsf{ID}_1, \cdots, \mathsf{ID}_j, \cdots, \mathsf{ID}_k)$ to denote a hierarchy of k n-bit string ID_j's. We write ID_j as ℓ blocks each of length n/ℓ bits $(\mathsf{ID}_{j,1}, \cdots, \mathsf{ID}_{j,\ell})$. We define $F_{\vec{U}_j}(\mathsf{ID}_j) = u'_j \prod_{i=1}^{\ell} u_{j,i}^{\mathsf{ID}_{j,i}}$.
- **Hash key for ciphertext validity:** choose an $(n+1)$-length vector $\vec{V} = (v', v_1, \cdots, v_n) \in_R \mathbb{G}^{n+1}$. This vector defines the hash function $F_{\vec{V}}(w) = v' \prod_{j=1}^{n} {v_j}^{b_j}$ where w is a n-bit string $b_1 b_2 \cdots b_n$.
- **Hash function:** pick a function $H : \{0,1\}^* \to \{0,1\}^n$ from a family of collision-resistant hash functions.

The public parameters Pub and the master secret key Msk are given by

$$\mathsf{Pub} = (\lambda, p, \mathbb{G}, \mathbb{G}_T, \hat{e}(\cdot,\cdot), n, \ell, g, g_1, g_2, \vec{U}_1, \cdots, \vec{U}_h, \vec{V}, H(\cdot)), \qquad \mathsf{Msk} = g_2^\alpha.$$

We require the discrete logarithms (with respect to g) of all $\mathbb{G}$ elements in Pub except g, g_1 to be unknown to the KGC. In practice, these elements can be generated from a pseudorandom function of a public seed.

$\mathsf{Extract}(d_{\vec{ID}}, \mathsf{ID}_r)$: For $\vec{ID} = (\mathsf{ID}_1, \cdots, \mathsf{ID}_k)$ for $k \leq h$, a trapdoor is in the form:

$$d_{\vec{ID}} = (a_1, a_2, \vec{Z}_{k+1}, \cdots, \vec{Z}_h) = (g_2^\alpha \cdot (\prod_{j=1}^{k} F_{\vec{U}_j}(\mathsf{ID}_j))^r, g^r, (\vec{U}_{k+1})^r, \cdots, (\vec{U}_h)^r),$$

where $r \in_R \mathbb{Z}_p^*$ and $(\vec{U}_j)^r = ((u'_j)^r, (u_{j,1})^r, \cdots, (u_{j,\ell})^r)$.

Note that (a_1, a_2) is sufficient for decryption, while $\vec{Z}_{k+1}, \cdots, \vec{Z}_h$ can help the derivation of the trapdoor for $(\mathsf{ID}_1, \cdots, \mathsf{ID}_k, \mathsf{ID}_{k+1})$ for any n-bit string ID_{k+1} and $k+1 \leq h$. To generate $d_{\vec{ID}||\mathsf{ID}_r}$ parse $d_{\vec{ID}} = (a_1, a_2, (z_{k+1}, z_{k+1,1}, \cdots, z_{k+1,\ell}),$

$\cdots, (z_h, z_{h,1}, \cdots, z_{h,\ell}))$ and parse ID_r as ℓ blocks $(\mathsf{ID}_{r,1}, \cdots, \mathsf{ID}_{r,\ell})$ where each block is of length n/ℓ bits, pick $t \in_R \mathbb{Z}_p^*$ and output

$$d_{\check{\vec{ID}}||\mathsf{ID}_r} = (a_1 \cdot z_{k+1} \prod_{i=1}^{\ell} (z_{k+1,i})^{\mathsf{ID}_{r,i}} \cdot (\prod_{j=1}^{k+1} F_{\check{\vec{U}}_j}(\mathsf{ID}_j))^t, a_2 \cdot g^t, \check{\vec{Z}}_{k+2} \cdot (\check{\vec{U}}_{k+2})^t \cdots, \check{\vec{Z}}_h \cdot (\check{\vec{U}}_h)^t$$

where the multiplication of two vectors are defined component-wise, i.e. $\check{\vec{Z}}_j \cdot \check{\vec{V}}_j = (z_j \cdot \nu_j, z_{j,1} \cdot \nu_{j,1}, \cdots, z_{j,\ell} \cdot \nu_{j,\ell})$. $d_{\check{\vec{ID}}}$ becomes shorter as the length of $\check{\vec{ID}}$ increases.

$\mathsf{KGen}()$: Pick $\mathsf{sk} \in_R \mathbb{Z}_p^*$, return $\mathsf{pk} = (X, Y) = (g^{\mathsf{sk}}, g_1^{\mathsf{sk}})$ and sk as the key pair.

$\mathsf{Enc}(m, \check{\vec{ID}}, \mathsf{pk})$: To encrypt $m \in \mathbb{G}_T$ for $\check{\vec{ID}} = (\mathsf{ID}_1, \cdots, \mathsf{ID}_k)$ where $k \leq h$, parse pk as (X, Y), then check that it is a valid public key by verifying[4] that $\hat{e}(X, g_1) = \hat{e}(g, Y)$. If equality holds, pick $s \in_R \mathbb{Z}_p^*$ and compute

$$C = (C_1, C_2, \tau, \sigma) = (m \cdot \hat{e}(Y, g_2)^s, \prod_{j=1}^{k} F_{\check{\vec{U}}_j}(\mathsf{ID}_j)^s, g^s, F_{\check{\vec{V}}}(w)^s)$$

where $w = H(C_1, C_2, \tau, \check{\vec{ID}}, \mathsf{pk})$.

$\mathsf{Dec}^S(C, d_{\check{\vec{ID}}})$: Parse C as (C_1, C_2, τ, σ), and $d_{\check{\vec{ID}}}$ as $(a_1, a_2, \cdots)$. First check if $\hat{e}(\tau, \prod_{j=1}^{k} F_{\check{\vec{U}}_j}(\mathsf{ID}_j) \cdot F_{\check{\vec{V}}}(w')) = \hat{e}(g, C_2 \cdot \sigma)$ where $w' = H(C_1, C_2, \tau, \check{\vec{ID}}, \mathsf{pk})$. Return $\perp$ if inequality holds or any parsing is not possible, otherwise pick $t \in_R \mathbb{Z}_p^*$ and return

$$D = (D_1, D_2, D_3) = (a_1 \cdot F_{\check{\vec{V}}}(w')^t, a_2, g^t).$$

$\mathsf{Dec}^U(C, \mathsf{sk}, D)$: Parse C as (C_1, C_2, τ, σ) and check if $\hat{e}(\tau, \prod_{j=1}^{k} F_{\check{\vec{U}}_j}(\mathsf{ID}_j) \cdot F_{\check{\vec{V}}}(w')) = \hat{e}(g, C_2 \cdot \sigma)$ where $w' = H(C_1, C_2, \tau, \check{\vec{ID}}, \mathsf{pk})$. If equality does not hold or parsing is not possible, return $\perp_C$. Next, parse D as (D_1, D_2, D_3) and check if $\hat{e}(g, D_1) = \hat{e}(g_1, g_2)\hat{e}(D_2, \prod_{j=1}^{k} F_{\check{\vec{U}}_j}(\mathsf{ID}_j))\hat{e}(D_3, F_{\check{\vec{V}}}(w'))$[5]. If equality does not hold or parsing is not possible, return $\perp_D$. Otherwise, return

$$m \leftarrow C_1 \cdot \left(\frac{\hat{e}(C_2, D_2)\hat{e}(\sigma, D_3)}{\hat{e}(\tau, D_1)} \right)^{\mathsf{sk}}.$$

[4] One pairing computation can be saved by a trick adopted in [20]: pick $\xi \in_R \mathbb{Z}_p^*$ and compute $C_1 = m \cdot \hat{e}(Y, g_2 \cdot g^{\xi})^s / \hat{e}(X, g_1^{s\xi})$.

[5] The same trick for minimizing the number of pairing computations involved in checking the ciphertext and the token can be incorporated to the final decryption step. The modified decryption algorithm only uses 4 pairing computations; however, it gives a random message (instead of an invalid flag $\perp$) for an invalid ciphertext.

4.3 Analysis

Like the HIBE scheme of Boneh, Boyen and Goh [6], the size of the ciphertext of our SMCLE scheme is independent of the hierarchy length. When the scheme is used as a TRE, the ciphertext size is not affected by the benefit brought by the hierarchy which minimizes the trapdoor size (see Section 5.5).

In the concrete SMCLE scheme of Chow, Boyd and González Nieto [15], partial decryption uses the pairing function $\hat{e}(\cdot,\cdot)$ to pair part of the ciphertext and the ID-based private key. To make this partial decryption result verifiable requires turning a generic interactive proof-of-knowledge non-interactive. Our scheme employs a different technique such that the token generated by the partial decryption is publicly and non-interactively verifiable.

Our scheme's security is asserted by Theorem 2; [16] contains a proof.

Theorem 2 *Our scheme is secure against Type-I attack and Type-II attack (Definition 3 and 4) if h-wDHI problem and 3-DDH problem is intractable.*

5 Applying General Certificateless Encryption to Timed-Release Encryption

5.1 Syntax of Timed-Release Encryption

For ease of discussion, consider only 1-level of time-identifiers as in [9]. It can be shown that our results hold for an h-level analog.

Definition 8. *A TRE scheme for time-identifiers of length n (n is a polynomially-bounded function) is defined by the following sextuple of* PPT *algorithms:*

- Setup *(run by the server) is a probabilistic algorithm which takes a security parameter* 1^λ*, outputs a master secret key* Msk*, and the global parameters* Pub*. We assume that* λ *and* $n = n(\lambda)$ *are implicit in* Pub *and all other algorithms take* Pub *implicitly as an input.*
- Extract *(run by the server) is a possibly probabilistic algorithm which takes the master secret key* Msk *and a string* $\mathsf{ID} \in \{0,1\}^n$*, outputs a trapdoor key* d_{ID} *associated with the identifier* ID*.*
- KGen *(run by a user) is a probabilistic algorithm which generates a public/private key pair* $(\mathsf{pk}_u, \mathsf{sk}_u)$*.*
- Enc *(run by a sender) is a probabilistic algorithm which takes a message* m *from some implicit message space, an identifier* $\mathsf{ID} \in \{0,1\}^n$*, and the receiver's public key* pk_u *as input, returns a ciphertext* C*.*
- Dec^S *(run by any one who holds the trapdoor, either a SEM or a receiver) is a possibly probabilistic algorithm which takes a ciphertext* C *and a trapdoor key* d_{ID} *as input, returns either a token* D *which can be seen as a partial decryption of* C*, or an invalid flag* $\perp$ *(which is not in the message space).*
- Dec^U *(run by a receiver) is a possibly probabilistic algorithm which takes the ciphertext* C*, the receiver's secret key* sk_u *and a token* D *as input, returns either the plaintext, an invalid flag* $\perp_D$ *denoting* D *is an invalid token, or an invalid flag* $\perp_C$ *denoting the ciphertext is invalid.*

For correctness, we require that $\mathsf{Dec}^U(C, \mathsf{sk}, \mathsf{Dec}^S(C, \mathsf{Extract}(\mathsf{Msk}, \mathsf{ID}))) = m$ *for all* $\lambda \in \mathbb{N}$, *all* $(\mathsf{Pub}, \mathsf{Msk}) \xleftarrow{\$} \mathsf{Setup}(1^\lambda)$, *all* $(\mathsf{pk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{KGen}$, *all message* m, *all identifier* ID *in* $\{0,1\}^n$ *and all* $C \xleftarrow{\$} \mathsf{Enc}(m, \mathsf{ID}, \mathsf{pk})$.

5.2 Timed-Release Encryption from Certificateless Encryption

Given a SMCLE scheme $\{\mathcal{SMC}.\mathsf{Setup}, \mathcal{SMC}.\mathsf{Extract}, \mathcal{SMC}.\mathsf{KGen}, \mathcal{SMC}.\mathsf{Enc}, \mathcal{SMC}.\mathsf{Dec}^S, \mathcal{SMC}.\mathsf{Dec}^U\}$, a TRE scheme $\{\mathcal{TRE}.\mathsf{Setup}, \mathcal{TRE}.\mathsf{Extract}, \mathcal{TRE}.\mathsf{KGen}, \mathcal{TRE}.\mathsf{Enc}, \mathcal{TRE}.\mathsf{Dec}^S, \mathcal{TRE}.\mathsf{Dec}^U\}$ can be built as below.

$\mathcal{TRE}.\mathsf{Setup}(1^\lambda, n)$: Given a security parameter λ and the length of the time-identifier n, execute $(\mathsf{Msk}, \mathsf{Pub}) \leftarrow \mathcal{SMC}.\mathsf{Setup}(1^\lambda, n)$, retain Msk as the master secret key and publish Pub as the global parameters.

$\mathcal{TRE}.\mathsf{Extract}(\mathsf{Msk}, \mathsf{ID})$: For a time-identifier $\mathsf{ID} \in \{0,1\}^n$, the time-server returns $d_{\mathsf{ID}} \leftarrow \mathcal{SMC}.\mathsf{Extract}(\mathsf{Msk}, \mathsf{ID})$.

$\mathcal{TRE}.\mathsf{KGen}()$: Return $(\mathsf{sk}, \mathsf{pk}) \leftarrow \mathcal{SMC}.\mathsf{KGen}()$ as the user's key pair.

$\mathcal{TRE}.\mathsf{Enc}(m, \mathsf{ID}, \mathsf{pk})$: To encrypt $m \in \mathbb{G}_T$ for pk under the time $\mathsf{ID} \in \{0,1\}^n$, first perform any checking of pk that is required by the $\mathcal{SMC}$ scheme. If pk is a valid public key, return $\mathcal{SMC}.\mathsf{Enc}(m, \mathsf{ID}, \mathsf{pk})$.

$\mathcal{TRE}.\mathsf{Dec}^S(C, d_{\mathsf{ID}})$: To partially decrypt C by a time-dependent trapdoor d_{ID}, return $D \leftarrow \mathcal{SMC}.\mathsf{Dec}^S(C, d_{\mathsf{ID}})$.

$\mathcal{TRE}.\mathsf{Dec}^U(C, \mathsf{sk}, D)$: To decrypt C by the secret key sk and the token D, just return $\mathcal{SMC}.\mathsf{Dec}^U(C, \mathsf{sk}, D)$.

Theorem 3 *If* $\mathcal{SMC}$ *is an* 1*-level SMCLE scheme which is CCA-secure against Type-I adversary (Definition 3),* $\mathcal{TRE}$ *is CCA-secure against Type-I adversary.*

Theorem 4 *If* $\mathcal{SMC}$ *is an* 1*-level SMCLE scheme which is CCA-secure against Type-II adversary (Definition 4),* $\mathcal{TRE}$ *is CCA-secure against Type-II adversary.*

Proof. The security models of TRE can be found in [16]. We prove by contradiction. Suppose $\mathcal{A}$ is a Type-X adversary such that $|\Pr[\mathbf{Exp}_{\mathcal{A}}^{\mathsf{CCA}'-\mathsf{X}}(\lambda) = 1] - \frac{1}{2}| > \epsilon$, we construct an adversary $\mathcal{B}$ with $|\Pr[\mathbf{Exp}_{\mathcal{B}}^{\mathsf{CCA}-\mathsf{X}}(\lambda) = 1] - \frac{1}{2}| > \epsilon$ in the face of a SMCLE challenger $\mathcal{C}$ where the running times of $\mathcal{B}$ and $\mathcal{A}$ are equal.

Setup: When $\mathcal{C}$ gives $\mathcal{B}$ $(\mathsf{Pub}, \mathsf{Aux})$, $\mathcal{B}$ just forwards it to $\mathcal{A}$. The public key to be passed to $\mathcal{A}$ is either chosen from the a set of public key in Aux (in Type-II game), or chosen by $\mathcal{B}$ itself (in Type-I game).

First Phase of Queries: $\mathcal{B}$ forwards every request of $\mathcal{A}$ to the oracles of its own challenger $\mathcal{C}$. From the description of $\mathcal{TRE}$, we can see that every legitimate oracle query made by $\mathcal{A}$ can be answered faithfully.

Challenge: When $\mathcal{A}$ gives $\mathcal{B}$ $(m_0, m_1, \mathsf{pk}^*, \mathsf{ID}^*)$, $\mathcal{B}$ just forwards it to $\mathcal{C}$.

Second Phase of Queries: Again, $\mathcal{B}$ just forwards every request of $\mathcal{A}$ to the oracles of its own challenger $\mathcal{C}$. From the description of $\mathcal{TRE}$, it is easy to see that every oracle query which does not violate the restriction enforced by $\mathcal{A}$ also does not violate the restriction enforced by $\mathcal{C}$.

Output: Finally, $\mathcal{A}$ outputs a bit b, $\mathcal{B}$ forwards it to $\mathcal{C}$ as its own answer. The probability for $\mathcal{A}$ to win the TRE experiment simulated by $\mathcal{B}$ is equal to the probability for $\mathcal{B}$ to win the SMCLE game played against $\mathcal{C}$. It is easy to see that the running times of $\mathcal{A}$ and $\mathcal{B}$ are the same. □

These theorems show that the scheme presented in section 4 can be instantiated as a TRE scheme without a random oracle.

5.3 Certificateless Encryption from Timed-Release Encryption

One may expect that a general CLE can be constructed from any TRE. The usage of time-identifiers, however, is only one specific instantiation of the timed-release idea. Other formulations of TRE, different from Definition 8, exist; for example, in the TRE scheme [11] time is captured by the number of repeated computations of one-way hash function. Also, the notion of CLE supports an exponential number of arbitrary identifiers[6], so a CLE scheme cannot be realized by a TRE if the total number of time periods supported is too few.

There is an important difference in the definitions of security between CLE and TRE: the public keys in TRE are *certified* while there is no certification in CLE, so public keys can be chosen adversarially. Typically in TRE [5, 10, 13, 21, 26], a single public key is *given* to the adversary as the target of attack. However, the non-standard TRE formulation in [9] does allow uncertified public keys.

5.4 Security-Mediator in Timed-Release Encryption

The introduction of a security-mediator to the TRE paradigm gives a new business model for the time-server due to the support for partial decryption. Traditional TRE allows the time-server to release only a system-wide time-dependent trapdoor. The time-server can charge for each partial decryption request of a ciphertext by the time-dependent trapdoor; the partial decryption of one ciphertext would not help the decryption of any other ciphertext.

5.5 Time Hierarchy

Since each identifier corresponds to a single time period, the server must publish t private keys once t time-periods have passed. The amount of data that must be posted can be reduced given a hierarchical CLE by using the CHK forward secure encryption scheme [8] in reverse [6]. For a total of T time periods, the

[6] Even though the scheme may be insecure when more than a polynomial number of trapdoors are compromised by a single adversary.

CHK framework is set up as a tree of depth $\log T$. To encrypt a message for time $t < T$, the time identifier is the CHK identifier for time period $T - t$. Release of trapdoor is done in the same manner: the private key for the time period $T - t$ is released on the t^{th} time period. This single private key enables anyone to derive the private keys for CHK time periods $T - t, T - t + 1, \cdots, T$, so the user can obtain trapdoors for times $1, \cdots, t$. This trick enables the server to publish only a single private key of $O(\log^2 T)$ group elements at any time.

6 Conclusions

Cryptographers seek and try to achieve the strongest possible security definition. Previous models of certificateless encryption (CLE) were too restrictive: they could not give the desired security properties when instantiated as timed-release encryption (TRE). Our generalized CLE model supports the requirements of TRE; all future CLE proposals in our general model automatically give secure TRE schemes. Our model is defined against full-identifier extraction, decryption under arbitrary public key, and partial decryption, to achieve strong security. Our concrete scheme yields the first strongly-secure (hierarchical) security-mediated CLE and the first TRE in the standard model.

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