

A New Practical Identity-Based Encryption System

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Abstract

We present a new practical Identity-Based Encryption (IBE) system that can be another candidate for standard IBE techniques. Our construction is based on a new framework for realizing an IBE trapdoor from pairing-based groups, which is motivated from the ‘two equation’ revocation technique suggested by Lewko, Sahai, and Waters. The new framework enables our IBE system to achieve a tight security reduction to the standard Decision Bilinear Diffie-Hellman assumption. Due to its tightness, our system can take as input the shorter size of security parameters than the previous practical BF, SK, and BB_1 systems, which provides better efficiency to our system in terms of computational cost. With appropriate parametrization at the current 80-bit security level, our IBE system can obtain 11 times faster decryption than the previous ones and 77 times faster encryption than the BF system. We prove that our system is fully secure against chosen ciphertext attacks in the random oracle model. From computational variant of Naor’s observation, we can also suggest a new signature scheme that features a tight security reduction to the Computational Diffie-Hellman assumption and provides strong unforgeability simultaneously.

Keywords: Identity-based encryption, Bilinear maps.

1 Introduction

Identity-Based Encryption (IBE) [47] is a special type of public key encryption where a public key can be any string that carries its own meaning to a user’s identity, such as an e-mail address. As such a meaningful string can be naturally associated with a user, an IBE system does not need a certifying mechanism to ensure that a public key (as the meaningful string) is bound to a user (as the owner of the public key). As opposed to an IBE system, a traditional public key encryption system needs the certifying mechanism to securely distribute private keys, and indeed it must run on a complex architecture called ‘Public Key Infrastructure’.

By virtue of the advantage over the public key encryption, IBE had received considerable interest to cryptographic researchers since Shamir [47] posed the initial question about the existence of such an IBE system. In 2001, Boneh and Franklin [15] proposed the first practical IBE system based on groups with efficiently computable bilinear maps (i.e., pairings), along with a formal security definition of IBE. Since then, a large body of work [45, 24, 25, 10, 48, 31, 40, 41, 49] has been devoted to constructing pairing-based IBE systems to improve in terms of security and efficiency. Among the previous IBE systems, three of them have been perceived as practical constructions, which are works by Boneh-Franklin [15], Sakai-Kasahara [45, 24, 25], and Boneh-Boyen¹ [10], and thereafter they have been submitted to the IEEE P1363.3 standard for ‘Identity-Based Cryptographic Techniques using Pairings’.

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¹This is denoted as ‘ BB_1 ’.

1.1 Our Contribution

In this work we present a new practical IBE system that can be another candidate for standard IBE techniques. Our IBE system results from a new framework for realizing the IBE trapdoor, which is motivated by the ‘two equation’ technique recently suggested by Lewko, Sahai, and Waters [42]. One notable advantage of the new framework is that our construction is also pairing-based like BF, SK, and BB_1 systems, yet it has a *tight* security reduction to the standard Decision Bilinear Diffie-Hellman (DBDH) assumption. In order to encrypt arbitrary-length messages, we also suggest a new Identity-Based Key Encapsulation Mechanism (IBKEM) combined with one-time symmetric-key encryption. Our IBE systems are all proven to be fully secure against chosen ciphertext attacks in the random oracle model. In particular, one-time symmetric-key encryption secure against passive attacks is sufficient for the latter IBE system without the need of the ‘encrypt-then-MAC’ or ‘authenticated symmetric encryption’ paradigm.

Prior to our result, none of the three practical BF, SK, and BB_1 systems provided tightness in their respective security analysis, and in fact there existed significant security gaps between security assumptions and their IBE systems. One might wonder what the benefit from such tightness in security reduction is. The benefit is that we can achieve security of our system straightforwardly from that of the underlying DBDH assumption at the same security level. This means that if we want to instantiate our IBE system at current 80-bit security level, we can use a DBDH-hard group *at the same security level*. However, this is not the case in BF, SK, and BB_1 systems where security is loosely reduced to each security assumption by a factor of (at least) 2^{50} if we consider a reasonable number of adversarial hash queries as 2^{50} . The loose security reduction forces us to choose a larger security parameter (regarding DBDH-hard groups) than the 80-bit one even if we want to instantiate them at the 80-bit security level. Importantly, the larger security parameter tends to have an unfavorable effect on computational cost of resulting IBE systems [19]. For instance, when comparing BF, SK, and BB_1 systems at 128-bit security level with our system at an 80-bit security level, ours has about (at least) 11 times faster decryption than the three systems, and about 77 times faster encryption than the BF system. To add credence to this result, we give more concrete comparison results in terms of security reduction and efficiency in Section 5.

From variant of Naor’s observation (stated in [15]), our new framework gives rise to a new public-key signature scheme whose security relies on the standard Computational Diffie-Hellman (CDH) assumption in the random oracle model. Two favorable features of our signature scheme are that (1) it has a tight security reduction to the CDH assumption and (2) it is secure in the sense of strong unforgeability. BF, SK, and BB_1 systems also gave rise to signature schemes [17, 11, 48] derived from each one, but none of them have the two properties at the same time. It is also worth mentioning that it has been known that the Katz-Wang [35, 39] technique is only the one for the tightness of (1), but our result can give an alternative method.

1.2 Overview of Our New Technique

BF, SK, and BB_1 systems have their unique frameworks to realize IBE trapdoors from a pairing, respectively. Following Boyen’s naming in [19], each framework is called ‘full-domain-hash’ (for BF), ‘exponent-inversion’ (for SK), and ‘commutative-blinding’ (for BB_1). Each framework determines both the distinct structure of a private key and different kinds of security assumptions. Also, most of the subsequent pairing-based IBE systems fall into one of the three paradigms.

To build our new IBE system, we also come up with a new framework for realizing the IBE trapdoor. As we mentioned before, our framework is motivated by the two equation technique of Lewko, Sahai, and Waters [42]. Roughly speaking, the original LSW technique is to use private key elements $(g^r, (g_1 u^{\text{ID}})^r)$ and ciphertext elements $(g^s, (g_1 u^{\text{ID}'})^s)$ to compute a pairing value $e(g, u)^{sr}$. Here, g , g_1 , and u are from public

parameters. The value $e(g, u)^{sr}$ is then used to recover a message blinding factor $e(g, g)^{\alpha s}$ by pairing g^s with an additional key element $g^\alpha u^r$. The point is that such a pairing value can be obtained only if $ID \neq ID'$, and this gives the revocation system [42] where only users whose identities are different from ID' are able to compute the pairing value. On the other hand, our two equation technique is slightly changed in a way that computing the value $e(g, u)^{sr}$ is possible only if $ID = ID'$. This can be done by setting private key elements as $(g^r, (\mathcal{H}(ID)u^{\text{tag}_k})^r)$ and ciphertext elements as $(g^s, (\mathcal{H}(ID')u^{\text{tag}_c})^s)$, where \mathcal{H} is a cryptographic hash function and (as we explain below) the probability that $\text{tag}_k = \text{tag}_c$ is negligible.

As in the BF system, our framework requires a cryptographic hash function \mathcal{H} that maps an identity string $ID \in \{0, 1\}^*$ to a group element $\mathcal{H}(ID)$, but unlike the BF system a private key for an identity ID is not uniquely determined. A private key sk_{ID} consists of three groups $(g^\alpha u^r, g^r, (\mathcal{H}(ID)u^{\text{tag}_k})^r)$, which differs by a randomly-chosen exponent r in \mathbb{Z}_p . Here, α is the master secret key known only to a key generation center. At this moment, one may wonder how the value tag_k is decided. Indeed, we have that $\text{tag}_k = h(g^\alpha u^r, g^r) \in \mathbb{Z}_p$ by introducing another cryptographic hash function h . Similarly, when encrypting a message M , a ciphertext under ID is constructed as $(Me(g, g)^{\alpha s}, g^s, (\mathcal{H}(ID)u^{\text{tag}_c})^s)$ using the hash value $\text{tag}_c = h(Me(g, g)^{\alpha s}, g^s)$. In case of our IBKEM, an arbitrary length message M is encrypted as $(\mathcal{E}_K(M), g^s, (\mathcal{H}(ID)u^{\text{tag}_c})^s)$ using a one-time symmetric-key encryption algorithm \mathcal{E} , where $K = e(g, g)^{\alpha s}$ and $\text{tag}_c = h(\mathcal{E}_K(M), g^s)$. If we use a collision-resistant hash function h , the correctness error caused by the equality $\text{tag}_k = \text{tag}_c$ becomes acceptable in practice. Another characteristic of our framework is to use the hash function h to protect the ciphertext element $Me(g, g)^{\alpha s}$ or $\mathcal{E}_K(M)$ related to M . Indeed, the distinct usage of h enables our system to directly obtain chosen ciphertext security without resorting to other methods such as ‘encrypt-then-MAC’ or ‘authenticated symmetric encryption’.

We now explain how our IBE system can achieve a tight security reduction under the DBDH assumption. In our security proofs, the two hash functions \mathcal{H} and h are modeled as random oracles. Somewhat surprisingly, being able to use two hash functions in generating one group element enables our reduction algorithm to generate private keys for *all* identities and use *any* identity as a challenge identity ID^* . Nevertheless, a private key for ID^* is not helpful to decrypt the challenge ciphertext (that can be constructed under ID^*), which is necessary for solving the so-called ‘self-decryption’ paradox. Notice that similar reductions can be found in [31, 49] that provided full security without random oracles. Let (g, g^a, g^b, g^c, T) be a DBDH instance. Given an identity ID_i , the random oracle \mathcal{H} outputs $\mathcal{H}(ID_i) = (g^a)^{\gamma_i} g^{\pi_i}$ for two randomly-chosen exponents γ_i and π_i in \mathbb{Z}_p . The important point is that the value γ_i per each identity can be information-theoretically hidden from an adversary’s view and later used for an output value of another random oracle h . When creating a private key for ID_i , our reduction algorithm is able to generate the key as $(g^\alpha u^{\tilde{r}}, g^{\tilde{r}}, (\mathcal{H}(ID_i)u^{\text{tag}_k})^{\tilde{r}})$ by setting $\text{tag}_k = h(g^\alpha u^{\tilde{r}}, g^{\tilde{r}}) = \gamma_i$ and $\tilde{r} = b + r$ for a random r in \mathbb{Z}_p . The validity of the private key is checked under the condition that $\alpha = ab$ and $u = g^{-a}g^\delta$ for a random $\delta \in \mathbb{Z}_p$. A similar manipulation is taken when generating the challenge ciphertext under ID^* . As sk_{ID^*} must not be asked, the value γ^* embedded into $\mathcal{H}(ID^*)$ will be hidden until the challenge phase (with non-negligible probability) and thus can be reserved for setting $\text{tag}_c = \gamma^*$ (as well as $s = c$ for the DBDH problem). In case when trying to decrypt the challenge ciphertext using sk_{ID^*} , the decryption is not possible because $\text{tag}_k = \text{tag}_c$.

To achieve the chosen ciphertext security, our reduction algorithm needs to deal with adversarial decryption queries. In our security analysis, this is not a big problem as private keys for all identities can be generated and ill-formed ciphertexts are detected via consistency check using pairing. The only problem is that in the event that $\text{tag}_k = \text{tag}_c$ happens, normal decryption cannot be performed. However, as an output of h as a random oracle is determined by choosing a random value in \mathbb{Z}_p and p is exponentially large (e.g., p is a 160-bit prime), our reduction can avoid such a troublesome case in all decryption queries (with non-negligible probability).

1.3 Related Work

Boneh and Franklin [15] presented the first practical IBE system based on groups with efficiently computable pairings and defined the formal security notion for IBE known as full security against chosen ciphertext attacks. Most of the subsequent IBE systems followed the notion depending on different kinds of security assumptions. Until now, BF[15], SK[45, 24, 25], and BB_1 [10] systems have been considered as practical constructions and their security was all demonstrated in the random oracle model.

In an attempt to prove security without random oracles, Canetti et al. [21] suggested a weaker security notion for IBE, known as selective-ID security. Following the weaker notion, Boneh and Boyen [10] proposed two efficient IBE systems, one of which was the basis for BB_1 . Many IBE systems [48, 31, 40, 41, 49] were later suggested to achieve full security without random oracles, but they all become less efficient than the random oracle constructions in practical aspects such as public parameter size or achieving chosen ciphertext security.

Regarding tight security reduction, Attrapadung et al.[5] proposed a Katz-Wang variant of the BF system whose security is tightly reduced to the DBDH assumption. Their construction is fully secure against chosen ciphertext attacks in the random oracle model, but impractical especially in terms of both encryption and decryption costs. On the other hand, Gentry IBE [31] achieved the full security without random oracles. Tightness in its security reduction was achieved by relying on a (non-standard) q -type assumption where q depends on the number of private key queries that an adversary makes.

The notion of IBE has been extended in two flavors. In a vertical (and hierarchical) extension, IBE can provide a ‘delegation’ mechanism [38, 34] by which private keys for lower-level identities are created from an upper-level identity but the reverse is not possible. Many works [34, 10, 12, 48, 20, 46, 32, 49] have been suggested to realize such a delegation mechanism, also known as Hierarchical IBE (HIBE). In a horizontal extension, IBE becomes the special case of the Attribute-Based Encryption (ABE) [44, 37, 9], where attributes (instead of a single identity) are associated with private keys and ciphertexts, respectively, and decryption works only if attributes satisfy a function depending on each ABE system. Furthermore, when attributes (an identity) embedded into ciphertexts are encrypted, ABE (IBE) can also be extended for providing searchable techniques [14, 1] on encrypted data. Recently, the horizontal extensions are conceptually united under the notion of Functional Encryption (FE) [18].

Finally, we notice that there exist other approaches to build IBE trapdoors without pairings. Cocks [26] and Boneh et al. [16] constructed IBE systems based on the quadratic-residuosity problem and Gentry et al. [33] demonstrated how to build an IBE system based on lattice. Recently, lattice-based IBE can also be extended toward HIBE [23, 2, 3] and FE [4] constructions.

2 Preliminaries

2.1 Identity-Based Encryption

An Identity-Based Encryption (IBE) system consists of four algorithms:

- **Setup**(k) takes a security parameter k as input and outputs a public parameter PP and a master secret key msk .
- **KeyGen**(msk, PP, ID) takes a master secret key msk , a public parameter PP and an identity $ID \in \mathcal{ID}$ as inputs, where \mathcal{ID} is an identity space. It outputs sk_{ID} , a private key for ID .

- **Encrypt**(PP, M , ID') takes a public parameter PP, a message $M \in \mathcal{M}$, and an identity ID $\in \mathcal{ID}$ as inputs, where \mathcal{M} is a message space. It outputs CT under ID, a ciphertext under ID.
- **Decrypt**(CT, PP, sk_{ID}) takes a ciphertext CT under ID', a public parameter PP, and a private key sk_{ID} as inputs. If ID' = ID, it outputs a message M .

Correctness. For all ID, ID' $\in \mathcal{ID}$ and all $M \in \mathcal{M}$, let $(PP, msk) \leftarrow \mathbf{Setup}(k)$, $sk_{ID} \leftarrow \mathbf{KeyGen}(msk, PP, ID)$, $CT \leftarrow \mathbf{Encrypt}(PP, M, ID')$. If ID' = ID, we have $M \leftarrow \mathbf{Decrypt}(sk_{ID}, PP, CT)$ otherwise \perp .

We next define the chosen ciphertext security [15] of an IBE system, which is commonly accepted. The security is defined via the following game interacted by a challenger \mathcal{C} and an adversary \mathcal{A} :

- **Setup:** \mathcal{C} runs the setup algorithm to obtain a public parameter PP and a master secret key msk. \mathcal{C} gives PP to \mathcal{A} .
- **Query Phase 1:** \mathcal{A} adaptively issues a number of queries where each query is one of:
 - Private key query on ID: \mathcal{C} runs the key generation algorithm to obtain a private key for ID and gives the key sk_{ID} to \mathcal{A} .
 - Decryption query on (CT, ID): \mathcal{C} runs the key generation algorithm to obtain sk_{ID} to \mathcal{A} and then runs the decryption algorithm using CT_{ID} and sk_{ID} . It gives the resulting message to \mathcal{A} .
- **Challenge:** \mathcal{A} outputs two equal-length messages M_0, M_1 and an identity ID* on which it wishes to be challenged. The only restriction is that ID is not queried in Query Phase 1. \mathcal{C} flips a coin $\sigma \in \{0, 1\}$. \mathcal{C} gives $CT^* \leftarrow \mathbf{Encrypt}(PP, M_\sigma, ID^*)$ as a challenge ciphertext to \mathcal{A} .
- **Query Phase 2:** \mathcal{A} adaptively issues a number of additional queries where each query is one of:
 - Private key query on ID, where ID $\neq ID^*$: \mathcal{C} responds as in Query Phase 1.
 - Decryption query on (CT, ID), where (CT, ID) $\neq (CT^*, ID^*)$: \mathcal{C} responds as in Query Phase 1.
- **Guess:** \mathcal{A} outputs a guess $\sigma' \in \{0, 1\}$. \mathcal{A} wins if $\sigma' = \sigma$.

The advantage of the adversary \mathcal{A} in breaking the chosen ciphertext security of an IBE system \mathcal{IBE} is defined as $\mathbf{Adv}_{\mathcal{IBE}, \mathcal{A}}^{\text{CCA}} = |\Pr[b' = b] - 1/2|$.

Definition 1. We say that an IBE system is (t, ϵ, q_K, q_D) -IND-ID-CCA secure if for any polynomial time adversary \mathcal{A} that runs in time at most t , issues at most q_K private key queries and at most q_D decryption queries in chosen ciphertext security games, the advantage $\mathbf{Adv}_{\mathcal{IBE}, \mathcal{A}}^{\text{CCA}}$ is negligible.

2.2 One-time Symmetric-key Encryption

A one-time symmetric-key encryption scheme consists of two algorithms: a deterministic encryption algorithm \mathcal{E} takes a message $M \in \{0, 1\}^*$ and a key $K \in \mathcal{K}$ as inputs and outputs a ciphertext $C = \mathcal{E}_K(M)$. Here, \mathcal{K} is a key space that is determined by a security parameter $k \in \mathbb{Z}^+$. Another deterministic algorithm \mathcal{D} is a decryption algorithm that takes a ciphertext C and a key K as inputs and outputs a message $M = \mathcal{D}_K(C)$ or \perp .

We define security for a one-time symmetric-key encryption scheme $\mathcal{SKE} = (\mathcal{E}, \mathcal{D})$, which is security against *passive* attacks [27]. The security is defined via the following game interacted by a challenger \mathcal{C} and an adversary \mathcal{A} :

- **Setup:** \mathcal{C} chooses a random key K in key space $\mathcal{K}(k)$.
- **Challenge:** \mathcal{A} outputs two equal-length messages M_0 and M_1 . \mathcal{C} flips a coin $\sigma \in \{0, 1\}$ and gives $C^* \leftarrow \mathcal{E}_K(M_\sigma)$ as a challenge ciphertext to \mathcal{A} .
- **Guess:** \mathcal{A} outputs a guess $\sigma' \in \{0, 1\}$. \mathcal{A} wins if $\sigma' = \sigma$.

The advantage of the adversary \mathcal{A} in breaking the passive security of a one-time symmetric-key encryption scheme $\mathcal{SK}\mathcal{E}$ is defined as $\text{Adv}_{\mathcal{SK}\mathcal{E}, \mathcal{A}}^{\text{OT-IND}} = |\Pr[b' = b] - 1/2|$.

Definition 2. We say that a one-time symmetric-key encryption scheme is (t, ϵ) -secure against passive attacks if for any polynomial time adversary \mathcal{A} that runs in time at most t in passive attack games, the advantage $\text{Adv}_{\mathcal{SK}\mathcal{E}, \mathcal{A}}^{\text{OT-IND}}$ is negligible.

2.3 Bilinear Pairings and Complexity Assumption

We briefly review bilinear pairings and the complexity assumption. Here, we simply consider symmetric pairings in prime-order groups.

Bilinear Pairings: We follow the standard notation in [15, 10]. Let \mathbb{G} and \mathbb{G}_T be two (multiplicative) cyclic groups of prime order p . We assume that g is a generator of \mathbb{G} . Let $e : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ be a function that has the following properties:

1. Bilinear: for all $u, v \in \mathbb{G}$ and $a, b \in \mathbb{Z}$, we have $e(u^a, v^b) = e(u, v)^{ab}$.
2. Non-degenerate: $e(g, g) \neq 1$.
3. Computable: there is an efficient algorithm to compute the map e .

Then, we say that \mathbb{G} is a bilinear group and the map e is a bilinear pairing in \mathbb{G} . Note that $e(\cdot, \cdot)$ is symmetric since $e(g^a, g^b) = e(g, g)^{ab} = e(g^b, g^a)$.

The Decisional Bilinear Diffie-Hellman (DBDH) Problem: The DBDH problem [15] is defined as follows: given $(g, g^a, g^b, g^c, T) \in \mathbb{G}^4 \times \mathbb{G}_T$ as input, output 1 if $T = e(g, g)^{abc}$ and 0 otherwise. We say that an algorithm \mathcal{A} that outputs $\sigma \in \{0, 1\}$ has an advantage $\text{Adv}_{\mathbb{G}, \mathcal{A}}^{\text{DBDH}} = \epsilon$ in solving the DBDH problem in \mathbb{G} if

$$\left| \Pr[\mathcal{A}(g, g^a, g^b, g^c, e(g, g)^{abc}) = 0] - \Pr[\mathcal{A}(g, g^a, g^b, g^c, R) = 0] \right| \geq \epsilon,$$

where the probability is taken over the random choice of $a, b, c \in \mathbb{Z}_p$, the random choice of $R \in \mathbb{G}_T$, and the random bits used by \mathcal{A} .

Definition 3. We say that the (t, ϵ) -DBDH assumption holds in \mathbb{G} if for any polynomial time adversary \mathcal{A} that runs in time at most t in solving the DBDH problem in \mathbb{G} , the advantage $\text{Adv}_{\mathbb{G}, \mathcal{A}}^{\text{DBDH}}$ is negligible.

3 Our IBE System

3.1 Construction

Setup(k): Given a security parameter $k \in \mathbb{Z}^+$, the setup algorithm runs $\mathcal{G}(k)$ to obtain a tuple $(p, \mathbb{G}, \mathbb{G}_T, e)$. The algorithm selects a random generator $g \in \mathbb{G}$, a random group element $u \in \mathbb{G}$, and a random exponent $\alpha \in \mathbb{Z}_p$. The algorithm sets $A = e(g, g)^\alpha$ and chooses two cryptographic hash functions $H_1 : \{0, 1\}^* \rightarrow \mathbb{G}$

and $H_2 : \{0, 1\}^* \rightarrow \mathbb{Z}_p$. The public parameters PP (with the description of $(p, \mathbb{G}, \mathbb{G}_T, e)$) and the master secret key msk are generated as

$$\text{PP} = (g, u, A, H_1, H_2), \quad \text{msk} = \alpha.$$

KeyGen(msk, PP, ID): To create a private key sk_{ID} for an identity $\text{ID} \in \mathcal{ID}$, the key generation algorithm does the following:

1. Pick a random exponent $r \in \mathbb{Z}_p$.
2. Compute $d_0 = g^\alpha u^r$, $d_1 = g^r$, and $\text{tag}_k = H_2(d_0, d_1) \in \mathbb{Z}_p$.
3. Compute $d_2 = (H_1(\text{ID})u^{\text{tag}_k})^r$.
4. Output a private key $\text{sk}_{\text{ID}} = (d_0, d_1, d_2) \in \mathbb{G}^3$.

Encrypt(PP, ID, M): To encrypt a message $M \in \mathbb{G}_T$ under an identity $\text{ID} \in \mathcal{ID}$, the encryption algorithm does as follows:

1. Pick a random exponent $s \in \mathbb{Z}_p$.
2. Compute $C_0 = MA^s$, $C_1 = g^s$, and $\text{tag}_c = H_2(C_0, C_1) \in \mathbb{Z}_p$.
3. Compute $C_2 = (H_1(\text{ID})u^{\text{tag}_c})^s$.
4. Output a ciphertext $\text{CT} = (C_0, C_1, C_2) \in \mathbb{G}_T \times \mathbb{G}^2$.

Decrypt(PP, CT, sk_{ID}): To decrypt a ciphertext $\text{CT} = (C_0, C_1, C_2)$ using a private key $\text{sk}_{\text{ID}} = (d_0, d_1, d_2)$ for ID, the decryption algorithm does as follows:

1. Compute $\text{tag}_c = H_2(C_0, C_1)$ and $\text{tag}_k = H_2(d_0, d_1)$.
2. Check if $e(H_1(\text{ID})u^{\text{tag}_c}, C_1) \stackrel{?}{=} e(C_2, g)$.
3. If the equality above fails, output \perp .
4. Otherwise, check if $\text{tag}_c \stackrel{?}{=} \text{tag}_k$.
5. If the equality above holds, output \perp .
6. Otherwise, compute

$$M = C_0 / e(d_0, C_1) \cdot \left(\frac{e(C_2, d_1)}{e(d_2, C_1)} \right)^{\frac{-1}{\text{tag}_c - \text{tag}_k}}. \quad (1)$$

Correctness. If $\text{tag}_c \neq \text{tag}_k$, we can verify that the decryption algorithm works correctly for well-formed ciphertexts as follows:

$$\begin{aligned} e(d_0, C_1) \cdot \left(\frac{e(C_2, d_1)}{e(d_2, C_1)} \right)^{\frac{-1}{\text{tag}_c - \text{tag}_k}} &= e(g^\alpha u^r, g^s) \cdot \left(\frac{e((H_1(\text{ID})u^{\text{tag}_c})^s, g^r)}{e((H_1(\text{ID})u^{\text{tag}_k})^r, g^s)} \right)^{\frac{-1}{\text{tag}_c - \text{tag}_k}} \\ &= e(g, g^\alpha)^s e(u, g)^{sr} \cdot e(u^{\text{tag}_c - \text{tag}_k}, g^{sr})^{\frac{-1}{\text{tag}_c - \text{tag}_k}} \\ &= A^s. \end{aligned}$$

Encryption and decryption Costs. In encryption, the three exponentiations A^s , g^s , and $u^{\text{tag}_c \cdot s}$ can be calculated in fixed bases A , g , and u , respectively. Instead, the hashing $H_1(\text{ID})$ and its exponentiation $H_1(\text{ID})^s$ will be done separately without precomputation in usual situations. Thus, the encryption cost becomes 3 fixed-base exponentiations plus 1 hashing and 1 general exponentiation.

Upon decryption, it seems that the decryption algorithm requires computing 5 pairings, but these can be saved into 1.2 pairings. We first can change the above formula (1) into:

$$e(d_0, C_1) \cdot \left(\frac{e(C_2, d_1)}{e(d_2, C_1)} \right)^{\frac{-1}{\text{tag}_c - \text{tag}_k}} = \frac{e\left(C_2, d_1^{\frac{-1}{\text{tag}_c - \text{tag}_k}}\right)}{e\left(d_0^{-1} d_2^{\frac{-1}{\text{tag}_c - \text{tag}_k}}, C_1\right)}.$$

Next, by using the *implicit* consistency check [40], we do not need to perform the pairing consistency test explicitly. Instead, the decryption algorithm randomizes two elements $H_1(\text{ID})u^{\text{tag}_c}$ and g by raising a randomly chosen exponent $\tilde{r} \in \mathbb{Z}_p$ and performs the following computation:

$$\frac{e\left(C_2, d_1^{\frac{-1}{\text{tag}_c - \text{tag}_k}} g^{\tilde{r}}\right)}{e\left(d_0^{-1} d_2^{\frac{-1}{\text{tag}_c - \text{tag}_k}} (H_1(\text{ID})u^{\text{tag}_c})^{\tilde{r}}, C_1\right)}. \quad (2)$$

If the pairing test passes, the output of the above equation becomes the same as that of the original decryption algorithm. Otherwise, the fresh random value \tilde{r} chosen by the decryption algorithm survives and thus prevents an adversary from gaining any information on an ill-formed ciphertext. As a consequence, the decryption cost is determined by the computation in the equation (2) that shows five exponentiations and two pairing computations. All the exponentiations can be done in fixed bases such as g , d_1 , d_2 , u , and $H_1(\text{ID})$. Notice that a user with identity ID can compute $H_1(\text{ID}) \in \mathbb{G}$ and prepare for fixed bases related with it, regardless of any received ciphertext. Also, a ratio of two pairings can be estimated into 1.2 pairings [19]. Thus, the decryption cost is concluded with 5 fixed-base exponentiations plus 1.2 pairings.

Achieving Perfect Correctness. Upon decryption, our decryption algorithm cannot proceed in the event that $\text{tag}_c = \text{tag}_k$ occurs. Obviously, the probability that the event happens is negligible when the value tag is in \mathbb{Z}_p and p is represented by approximately 160 bits. However, in order to avoid even the negligible correctness error, we can locate a suitable approach in a recent tag-based dual system encryption [49] where a similar decryption process to ours appears. A possible solution is to simply run an efficient selectively (chosen-ciphertext) secure IBE system [10] in parallel. When a message is encrypted under ID with tag_c , an encryptor also encrypts the message under the tag_c in the second selective system. When the two tags are different, we can use our original IBE system. In the unlikely event that the two tags are equal, we can use the second ciphertext. An alternative approach in [49] such as giving two private keys for an identity ID seems to not be applicable to our system, because we can assign a hash value $H_1(\text{ID})$ to only one tag value in our security analysis.

Construction under Asymmetric Pairings. The system can be instantiated in asymmetric bilinear groups where we have asymmetric pairing $e : \mathbb{G} \times \widehat{\mathbb{G}} \rightarrow \mathbb{G}_T$ defined over different groups \mathbb{G} and $\widehat{\mathbb{G}}$. In that case, we need to hash an identity into a group element in either \mathbb{G} or $\widehat{\mathbb{G}}$. If we choose \mathbb{G} , then a private key consists of group elements in $\mathbb{G} \times \widehat{\mathbb{G}} \times \mathbb{G}$ and a ciphertext has elements in $\mathbb{G}_T \times \widehat{\mathbb{G}} \times \mathbb{G}$. The reverse is also possible, and the selection of each option affects the efficiency of the IBE system when instantiated with MNT curves [19].

3.2 Security

Theorem 1. Let H_1 and H_2 be modeled as random oracles. Suppose the (t', ϵ') -DBDH assumption holds in \mathbb{G} . Then our IBE system is (t, ϵ, q_K, q_D) -IND-ID-CCA secure, where

$$\epsilon \leq \left(1 - \left(\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}\right)\right) \cdot \epsilon',$$

$$t \geq t' - \mathcal{O}(q_K \cdot t_e) - \mathcal{O}(q_D \cdot t_p).$$

Here, t_e is the cost of an exponentiation in \mathbb{G} and t_p is the cost of a pairing computation in \mathbb{G} .

Proof. Suppose that there exists an adversary \mathcal{A} which can break the CCA security of our IBE system. We can then build an algorithm \mathcal{B} which uses \mathcal{A} to solve a DBDH problem in \mathbb{G} . On input (g, g^a, g^b, g^c, T) , \mathcal{B} attempts to output 1 if $T = e(g, g)^{abc}$ and 0 otherwise. \mathcal{B} interacts with \mathcal{A} as follows.

Setup \mathcal{B} selects a random element $\delta \in \mathbb{Z}_p$ and sets $u = g^{-a}g^\delta$ and $A = e(g^a, g^b)$. Note that $\alpha = ab \in \mathbb{Z}_p$, which is unknown to \mathcal{B} . Then, \mathcal{A} is given the public key $\text{PK} = (g, u, A, H_1, H_2)$, where H_1 and H_2 are modeled as random oracles.

Query Phase 1 \mathcal{A} issues H_1 , H_2 , private key, and decryption queries. \mathcal{B} responds as follows:

H_1 queries: To respond to H_1 queries, \mathcal{B} maintains a list of tuples $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$ as explained below. We refer to this list as the H_1^{list} . When \mathcal{B} is given an identity ID_i as an input to H_1 , \mathcal{B} first scans through the H_1^{list} to see if the input ID_i appears in a tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$. If it does, \mathcal{B} responds with $H_1(\text{ID}_i)$. Otherwise, \mathcal{B} picks two random exponents $\gamma_i, \pi_i \in \mathbb{Z}_p$ and sets $H_1(\text{ID}_i) = (g^a)^{\gamma_i} g^{\pi_i} \in \mathbb{G}$. \mathcal{B} adds the new tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$ to the H_1^{list} and responds with $H_1(\text{ID}_i)$. Recall that the values $\{\gamma_i\}$ are information-theoretically hidden to \mathcal{A} 's view.

H_2 queries: To respond to H_2 queries, \mathcal{B} maintains a list of tuples $\langle W_i, Q_i, \mu_i \rangle$ as explained below. We refer to this list as the H_2^{list} . When \mathcal{B} is given values (W_i, Q_i) , which is in either \mathbb{G}^2 or $\mathbb{G}_T \times \mathbb{G}$, as an input to H_2 , \mathcal{B} first scans through the H_2^{list} to see if the input (W_i, Q_i) appears in a tuple $\langle W_i, Q_i, \mu_i \rangle$. If it does, \mathcal{B} responds with $H_2(W_i, Q_i) = \mu_i$. Otherwise, \mathcal{B} picks a random exponent $\mu_i \in \mathbb{Z}_p$ and sets $H_2(W_i, Q_i) = \mu_i$. \mathcal{B} adds the new tuple $\langle W_i, Q_i, \mu_i \rangle$ to the H_2^{list} and responds with $H_2(W_i, Q_i)$.

Key queries: When \mathcal{B} is given an identity $\text{ID}_i \in \mathcal{ID}$ as an input to a private key query, \mathcal{B} selects a random exponent $r \in \mathbb{Z}_p$ and (implicitly) sets $\tilde{r} = b + r \in \mathbb{Z}_p$. \mathcal{B} generates key elements $(d_{0,i}, d_{1,i})$ as $d_{0,i} = (g^a)^{-r} (g^b)^\delta g^{\delta r}$ and $d_{1,i} = g^b g^r$. The validity of those elements can be verified as follows:

$$d_{0,i} = (g^a)^{-r} (g^b)^\delta g^{\delta r} = g^{ab} (g^{-a} g^\delta)^{b+r} = g^\alpha u^{\tilde{r}}, \quad d_{1,i} = g^b g^r = g^{\tilde{r}}.$$

Next, \mathcal{B} refers to the H_1^{list} to find out the tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$. (If no tuple exists, \mathcal{B} can run the H_1 -query process before replying to the key query.) At this moment, \mathcal{B} 's goal is to set $H_2(d_{0,i}, d_{1,i}) = \gamma_i$. Thus, if there is a tuple $\langle d_{0,i}, d_{1,i}, \gamma_i \rangle$ in the H_2^{list} , \mathcal{B} can continue the key query process. However, there could be the case where \mathcal{A} already issued $(d_{0,i}, d_{1,i})$ to the H_2 query and set $H_2(d_{0,i}, d_{1,i}) = \mu_i \neq \gamma_i$, in which case \mathcal{B} cannot generate the element $d_{2,i}$. To see whether there already exists the tuple $\langle d_{0,i}, d_{1,i}, \mu_i \rangle$ such that $\mu_i \neq \gamma_i$, \mathcal{B} refers to the H_2^{list} .

[Case 1.] If the tuple exists, \mathcal{B} aborts. (We refer to this event as abort1.)

[Case 2.] If the tuple does not exist, \mathcal{B} sets $H_2(d_{0,i}, d_{1,i}) = \gamma_i$ (where γ_i is from the tuple in the H_1^{list} above) and adds the tuple $\langle d_{0,i}, d_{1,i}, \gamma_i \rangle$ to the H_2^{list} . \mathcal{B} generates the element $d_{2,i}$, using $H_2(d_{0,i}, d_{1,i}) = \gamma_i$, as $d_{2,i} = (g^b)^{\pi_i + \gamma_i \delta} g^{(\pi_i + \gamma_i \delta)r}$. The validity of $d_{2,i}$ can be verified as follows:

$$d_{2,i} = (g^b)^{\pi_i + \gamma_i \delta} g^{(\pi_i + \gamma_i \delta)r} = ((g^a)^{\gamma_i} g^{\pi_i} \cdot (g^{-a + \delta})^{\gamma_i})^{b+r} = (H_1(\text{ID}_i) u^{H_2(d_{0,i}, d_{1,i})})^{\tilde{r}}.$$

Then, \mathcal{B} responds with a private key $\text{sk}_{\text{ID}_i} = (d_{0,i}, d_{1,i}, d_{2,i})$ for the requested identity ID_i .

Decryption queries: When \mathcal{B} is given a ciphertext $\text{CT}_i = (C_{0,i}, C_{1,i}, C_{2,i})$ (as well as an identity ID_i) as an input to a decryption query, \mathcal{B} first refers to the H_1^{list} to find out the tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$. (If no tuple exists, \mathcal{B} can run the H_1 -query process in advance as explained above.) Next, \mathcal{B} generates a private key $\text{sk}_{\text{ID}_i} = (d_{0,i}, d_{1,i}, d_{2,i})$ for the identity ID_i or uses the private key sk_{ID_i} that was generated before. During the key generation process, the event that \mathcal{B} aborts can take place as in the key queries. That is, there could already exist a tuple $\langle d_{0,i}, d_{1,i}, \mu_i \rangle$ in the H_2^{list} such that $H_2(d_{0,i}, d_{1,i}) = \mu_i \neq \gamma_i$. (We refer to this event as abort2.)

\mathcal{B} tries to perform normal decryption using sk_{ID_i} . Before checking whether $H_2(C_{0,i}, C_{1,i}) = \text{tag}_c \stackrel{?}{=} \text{tag}_k = H_2(d_{0,i}, d_{1,i})$, \mathcal{B} refers to the H_2^{list} to search for a tuple $\langle C_{0,i}, C_{1,i}, \tilde{\mu}_i \rangle$. If such a tuple regarding $(C_{0,i}, C_{1,i})$ does not exist, \mathcal{B} sets $H_2(C_{0,i}, C_{1,i}) = \tilde{\mu}_i$ by choosing a random $\tilde{\mu}_i \in \mathbb{Z}_p$ and adds the new tuple $\langle C_{0,i}, C_{1,i}, \tilde{\mu}_i \rangle$ to the H_2^{list} . Observe that in generating sk_{ID_i} , \mathcal{B} has to set $H_2(d_{0,i}, d_{1,i}) = \gamma_i$.

[Case 1.] If $\tilde{\mu}_i = \gamma_i$, \mathcal{B} aborts. (We refer to this event as abort3.) Notice that γ_i is from the tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$ in the H_1^{list} . In the real decryption, the equality means that $H_2(C_{0,i}, C_{1,i}) = \text{tag}_c = \text{tag}_k = H_2(d_{0,i}, d_{1,i})$ and thus the normal decryption is expected to output \perp , but \mathcal{B} simply aborts in our simulation. Thus, if the equality happens, \mathcal{A} can easily tell between the real attack and the simulation. We will give the reason below. Fortunately, the probability that the event abort3 happens is negligible while H_2 acts like a random oracle.

[Case 2.] If $\tilde{\mu}_i \neq \gamma_i$, \mathcal{B} performs the normal decryption using sk_{ID_i} and replies with the resulting message.

Challenge \mathcal{A} outputs two messages $M_0, M_1 \in \mathbb{G}_T$ and an identity ID^* on which it wishes to be challenged. If necessary, \mathcal{B} runs the algorithm for responding to H_1 query on ID^* . Let $\langle \text{ID}^*, \gamma^*, \pi^*, H_1(\text{ID}^*) \rangle$ be the tuple in the H_1^{list} regarding the challenged identity ID^* . Notice that \mathcal{A} cannot query a private key for ID^* . This means that the exponent γ^* in the tuple is not revealed to \mathcal{A} (with overwhelming probability) until the Challenge phase.

\mathcal{B} picks a random bit $\sigma \in \{0, 1\}$ and sets $C_0^* = M_\sigma T$ and $C_1^* = g^c$. It sets $H_2(C_0^*, C_1^*) = \gamma^*$. If the tuple $\langle C_0^*, C_1^*, \gamma_j \rangle$ are already in the H_2^{list} and $\gamma_j \neq \gamma^*$, then \mathcal{B} aborts. (We refer to this event as abort4.) Otherwise, \mathcal{B} generates the ciphertext $\text{CT}^* = (C_0^*, C_1^*, C_2^*) = (M_\sigma T, g^c, (g^c)^{\pi^* + \delta \gamma^*})$. \mathcal{B} (implicitly) sets $s = c$. The validity of C_2^* can then be verified as follows:

$$(g^c)^{\pi^* + \delta \gamma^*} = ((g^a)^{\gamma^*} g^{\pi^*} \cdot (g^{-a + \delta})^{\gamma^*})^c = (H_1(\text{ID}^*) u^{H_2(C_0^*, C_1^*)})^s.$$

Query Phase 2 \mathcal{A} issues more $\{H_i\}_{i=1,2}$, private key, and decryption queries. \mathcal{B} responds as in Query Phase 1. At this phase, however, there are challenging decryption queries \mathcal{B} has to deal with. That happens when \mathcal{A} issues *valid* ciphertexts such as $\text{CT}_i = (C_{0,i}, C_{1,i}^*, C_{2,i})$, where $C_{1,i}^*$ is the same as in CT^* . Here, we call a ciphertext $\text{CT} = (C_0, C_1, C_2)$ under an identity ID *valid* if the pairing test upon decryption holds, i.e., $e(H_1(\text{ID}) u^{H_2(C_0, C_1)}, C_1) = e(C_2, g)$. In such a case, \mathcal{B} should decrypt it correctly using the value $e(g, g)^{abc}$, which is infeasible. More precisely, there are four cases:

[Case 1.] $\text{CT}_i = (C_{0,i}^*, C_{1,i}^*, C_{2,i})$ on ID^* , where $C_{2,i} \neq C_2^*$. As the ciphertext is valid, it passes the pairing test upon decryption. Thus, \mathcal{B} has that $e(H_1(\text{ID}^*) u^{H_2(C_{0,i}^*, C_{1,i}^*)}, C_{2,i}) = e(C_{2,i}, g)$. Since $C_{1,i}^* = g^c$, the equation shows $C_{2,i} = (H_1(\text{ID}^*) u^{H_2(C_{0,i}^*, C_{1,i}^*)})^c$, which must be the same as C_2^* . This means that such a valid ciphertext in the form of $(C_{0,i}^*, C_{1,i}^*, C_{2,i})$ such that $C_{2,i} \neq C_2^*$ is not possible.

[Case 2.] $\text{CT}_i = (C_{0,i}, C_{1,i}^*, C_{2,i})$ on ID^* , where $C_{0,i} \neq C_0^*$. In this case, \mathcal{B} aborts. (We refer to this event as abort5.) Observe that this case can happen only if \mathcal{B} sets $H_2(C_{0,i}, C_{1,i}^*) = \gamma^* \in \mathbb{Z}_p$.

[Case 3.] $\text{CT}_i = (C_{0,i}, C_{1,i}^*, C_{2,i})$ on ID^* , where $C_{0,i} \neq C_0^*$ and $C_{2,i} \neq C_2^*$. As the ciphertext is valid, \mathcal{B} has that $e(H_1(\text{ID}^*) u^{H_2(C_{0,i}, C_{1,i}^*)}, C_{2,i}) = e(C_{2,i}, g)$. Since $C_{1,i}^* = g^c$, the equation shows $C_{2,i} = (H_1(\text{ID}^*) u^{H_2(C_{0,i}, C_{1,i}^*)})^c$.

Also, since $C_{2,i} \neq C_2^*$, we know that $H_2(C_{0,i}, C_1^*) \neq \gamma^*$. Then, \mathcal{B} has that

$$\begin{aligned} C_{2,i} &= (H_1(\text{ID}^*)u^{H_2(C_{0,i}, C_1^*)})^s = ((g^a)^\gamma g^\pi \cdot (g^{-a+\delta})^{H_2(C_{0,i}, C_1^*)})^c \\ &= (g^{ac})^{\gamma^* - H_2(C_{0,i}, C_1^*)} (g^c)^{\pi^* + \delta H_2(C_{0,i}, C_1^*)}, \end{aligned}$$

in which case \mathcal{B} can obtain g^{ac} by computing $[C_{2,i}/(C_1^*)^{\pi^* + \delta H_2(C_{0,i}, C_1^*)}]^{1/(\gamma^* - H_2(C_{0,i}, C_1^*))}$. It follows that \mathcal{B} can solve the given DBDH problem immediately.

[Case 4.] $\text{CT}_i = (C_{0,i}, C_1^*, C_{2,i})$ on $\text{ID} \neq \text{ID}^*$. Let $\langle \text{ID}, \gamma, \pi, H_1(\text{ID}) \rangle$ be the tuple in the H_1^{list} regarding ID . From the pairing test equation, \mathcal{B} has that $e(H_1(\text{ID})u^{H_2(C_{0,i}, C_1^*)}, C_1^*) = e(C_{2,i}, g)$. Since $C_1^* = g^c$, the equation shows that $C_{2,i} = (H_1(\text{ID})u^{H_2(C_{0,i}, C_1^*)})^c$. Notice that \mathcal{A} has not queried a private key for ID until the CT_i is queried. This is because as soon as \mathcal{A} is given the private key for ID , any decryption query regarding ID is not allowed under the rule of the security game. Therefore, the exponent γ in the tuple is not revealed to \mathcal{A} (with overwhelming probability) and \mathcal{B} has that $H_2(C_{0,i}, C_1^*) \neq \gamma$ with high probability. In the unlikely event that $H_2(C_{0,i}, C_1^*) = \gamma$, \mathcal{B} aborts. (We refer to this event as abort6.) Otherwise, \mathcal{B} has that

$$\begin{aligned} C_{2,i} &= (H_1(\text{ID})u^{H_2(C_{0,i}, C_1^*)})^s = ((g^a)^\gamma g^\pi \cdot (g^{-a+\delta})^{H_2(C_{0,i}, C_1^*)})^c \\ &= (g^{ac})^{\gamma - H_2(C_{0,i}, C_1^*)} (g^c)^{\pi + \delta H_2(C_{0,i}, C_1^*)}, \end{aligned}$$

in which case \mathcal{B} can obtain g^{ac} by computing $[C_{2,i}/(C_1^*)^{\pi + \delta H_2(C_{0,i}, C_1^*)}]^{1/(\gamma - H_2(C_{0,i}, C_1^*))}$. It follows that \mathcal{B} can solve the given DBDH problem immediately.

Guess \mathcal{A} outputs a guess $\sigma' \in \{0, 1\}$. \mathcal{B} then outputs its guess $\sigma' \in \{0, 1\}$ as the solution to the given DBDH instance.

Comment. The reason why \mathcal{B} aborts in the event abort3 is that the equality can leak the information on the input-output relation such that $H_2(d_0^*, d_1^*) = \gamma^*$, where γ^* is from the tuple $\langle \text{ID}^*, \gamma^*, \pi^*, H_1(\text{ID}^*) \rangle$ and (d_0^*, d_1^*) are from the private key $\text{sk}_{\text{ID}^*} = (d_0^*, d_1^*, d_2^*)$. Whenever \mathcal{A} issues a ciphertext $\text{CT}_i = (C_{0,i}, C_{1,i}, C_{2,i})$ (and the identity ID^*) as a decryption query, \mathcal{B} checks if $H_2(C_{0,i}, C_{1,i}) = \gamma^*$. If that is the case (and \mathcal{B} outputs \perp), \mathcal{A} is able to know that the value γ^* is used under the relation $H_2(d_0^*, d_1^*) = \gamma^*$, even though all elements in sk_{ID^*} are not revealed to \mathcal{A} . At this moment, however, \mathcal{A} can also observe that $H_2(C_0^*, C_1^*) = \gamma^*$ in the challenge ciphertext CT^* , which gives the knowledge that γ^* is used two times in both sk_{ID^*} and CT^* . Naturally, such a leakage can cause \mathcal{A} to distinguish between the simulation and the real attack.

Analysis. The dominated additional computation that \mathcal{B} requires is both the exponentiations for handling q_K private key queries and the pairings for handling q_D decryption queries. Thus, the inequality about computational time can easily be obtained.

Next, we assume Cases 3 and 4 described in the Query Phase 2 do not happen (which would rather increase \mathcal{B} 's success probability to solve the DBDH problem). To analyze \mathcal{B} 's advantage, we first prove the following claim that argues that the probability that \mathcal{B} aborts in the simulation is at most $\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}$, which is negligible.

Claim 1: $\Pr[\text{abort}] = \Pr[\text{abort1} \vee \text{abort2} \vee \text{abort3} \vee \text{abort4} \vee \text{abort5} \vee \text{abort6}]$ in the simulation is at most $\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}$.

Proof. The first equality is obvious since all events in the right-hand side are relatively independent. The event abort1 or abort2 can happen when the tuple $\langle d_{0,i}, d_{1,i}, \mu_i \rangle$ already exists but $\mu_i \neq \gamma_i$. Here, $d_{0,i}$ and $d_{1,i}$ are elements comprised of the private key sk_{ID_i} and γ_i is from the tuple $\langle \text{ID}_i, \gamma_i, \pi_i, H_1(\text{ID}_i) \rangle$ in the H_1^{list} . In those events \mathcal{B} wants to set $H_2(d_{0,i}, d_{1,i}) = \gamma_i$ by using the γ_i that is pre-determined but randomly

distributed from \mathcal{A} 's view. However, this setting is hindered by \mathcal{A} when \mathcal{A} makes H_2 query on the $(d_{0,i}, d_{1,i})$ before \mathcal{B} generates the same input values during key generation procedures. In other words, the events happen if the value $(d_{0,i}, d_{1,i})$ generated by \mathcal{B} exists in the H_2^{list} beforehand as an input value queried by \mathcal{A} . There are p possibilities of $(d_{0,i}, d_{1,i})$ values, since those are solely determined by a randomly chosen exponent in \mathbb{Z}_p . Therefore, for one input $(d_{0,i}, d_{1,i})$ generated, the probability that the event abort1 or abort2 happens is at most q_{H_2}/p , respectively. Since \mathcal{B} has to deal with at most $(q_K + q_D)$ H_2 queries, the probability that the events occur throughout the simulation becomes at most $q_{H_2}(q_K + q_D)/p$.

A similar argument can be made for the event abort4 when generating the challenge ciphertext. The event can occur if the value $(M_\sigma T, g^c)$ already exists in the H_2^{list} as the input value queried by \mathcal{A} . There are p possibilities in picking a value as an input to the H_2 query, because it only relates to one random exponent $c \in \mathbb{Z}_p$. This gives the probability at most q_{H_2}/p that the event abort4 happens.

Regarding the event abort3, the event happens if \mathcal{B} sets $H_2(C_{0,i}, C_{1,i}) = \gamma_i$ for any queried ciphertext $CT_i = (C_{0,i}, C_{1,i}, C_{2,i})$, where γ_i is from the tuple $\langle ID_i, \gamma_i, \pi_i, H_1(ID_i) \rangle$ in the H_1^{list} . γ_i is a pre-determined value and the output of H_2 query is just set by choosing a random value in \mathbb{Z}_p , so the probability that the event abort3 happens is at most $1/p$. Since \mathcal{B} has to handle q_D decryption queries, the probability that the event abort3 occurs throughout the simulation becomes at most q_D/p .

Regarding the event abort5, the event happens if \mathcal{B} sets $H_2(C_{0,i}, C_1^*) = \gamma^*$ for any queried ciphertext $CT_i = (C_{0,i}, C_1^*, C_2^*)$ on ID^* , where $C_{0,i} \neq C_0^*$. Also, regarding the event abort6, the event happens if \mathcal{B} sets $H_2(C_{0,i}, C_1^*) = \gamma$ for any queried ciphertext $CT_i = (C_{0,i}, C_1^*, C_2^*)$ on $ID \neq ID^*$. Here, the values γ^* and γ are pre-determined values. The output of H_2 query is just set by choosing a random value in \mathbb{Z}_p so that the probability that the event abort5 or abort6 happens is at most $1/p$, respectively. Since \mathcal{B} has to handle q_D decryption queries, the probability that the event abort5 or abort6 occurs throughout the simulation becomes at most $2q_D/p$.

All the events that \mathcal{B} aborts are relatively independent. As a result, the probability $\Pr[\text{abort1} \vee \text{abort2} \vee \text{abort3} \vee \text{abort4} \vee \text{abort5} \vee \text{abort6}]$ in the simulation is at most $\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}$. \square

From Claim 1, we can see that the probability that \mathcal{B} aborts in the simulation is negligible (under the appropriate selection of security parameters). This means that such an artificial abort is a negligible factor that cannot substantially affect the distinction between the simulation and the real attack. Therefore, as long as \mathcal{B} does not abort in the simulation, \mathcal{B} can use the \mathcal{A} 's advantage to break the chosen ciphertext security straightforwardly. This can be checked as follows: if $T = e(g, g)^{abc}$, then the challenge ciphertext CT^* is a valid encryption of M_σ under ID^* . Otherwise, i.e., if T is random in \mathbb{G}_T , then $M_\sigma T$ is independent of the bit σ . Thus, if \mathcal{A} distinguishes between the two ciphertexts, then \mathcal{B} can distinguish between the two possible values of T with the same probability. Thus, the the success probability of \mathcal{B} is given as follows:

$$\begin{aligned} \Pr[\mathcal{B} \text{ wins}] &= \Pr[\mathcal{B} \text{ wins} | \overline{\text{abort}}] \Pr[\overline{\text{abort}}] + \Pr[\mathcal{B} \text{ wins} | \text{abort}] \Pr[\text{abort}] \\ &= \Pr[\mathcal{B} \text{ wins} | \overline{\text{abort}}] \cdot (1 - \delta) + \Pr[\mathcal{B} \text{ wins} | \text{abort}] \cdot \delta \\ &\leq \Pr[\mathcal{A} \text{ wins}] \cdot (1 - \delta) + \frac{1}{2} \cdot \delta, \end{aligned}$$

where $\delta = \frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}$. For a security parameter k , we have the following result:

$$\mathbf{Adv}_{\mathbb{G}, \mathcal{B}}^{\text{DBDH}}(k) \leq (1 - \delta) \cdot \mathbf{Adv}_{\mathcal{I}, \mathcal{B}, \mathcal{E}, \mathcal{A}}^{\text{CCA}}(k),$$

as required. This concludes the proof of Theorem 1. \blacksquare

4 Extension for Arbitrary length Messages

In this section we extend our IBE system to deal with arbitrary length messages. Our extended system is based on the well-known framework using the key encapsulation mechanism (KEM) and data encapsulation mechanism (DEM). Identity-Based KEM (IBKEM) encrypts a symmetric key under which an arbitrarily long message is encrypted under a symmetric-key cipher DEM. Usually, to achieve CCA security of an entire IBE system, both IBKEM and DEM should be CCA-secure respectively [8] or DEM should be an authenticated symmetric-key encryption [41]. However, a slight difference resides in the part of DEM of our extended IBE system where it is sufficient for DEM to be a one-time symmetric-key encryption secure against passive attacks [27]. In practice, such a weak DEM can easily be instantiated with a block cipher using a so-called ‘counter mode’. The reason for the difference is that our IBE system is able to provide a consistency check (using pairing) to see if ciphertext elements including the DEM part are the same as what an encryptor constructed. We remark that a similar result concerning a weak DEM was achieved in [8] where BF-IBKEM is converted into a CCA-secure IBE system using the Fujisaki-Okamoto transform [29].

4.1 Construction

Setup(k): As in the previous IBE system. Additionally, the setup algorithm chooses a one-time symmetric-key encryption scheme $SK\mathcal{E} = (\mathcal{E}, \mathcal{D})$. The public parameters PP and the master secret key msk are generated as

$$PP = (g, u, A, H_1, H_2, SK\mathcal{E}), \quad msk = \alpha.$$

KeyGen(msk, PP, ID): As in the previous IBE system.

Encrypt(PP, ID, M): To encrypt an arbitrary length message $M \in \{0, 1\}^*$ under an identity $ID \in \mathcal{ID}$, the encryption algorithm does as follows:

1. Pick a random exponent $s \in \mathbb{Z}_p$.
2. Compute a key $K = A^s \in \mathbb{G}_T$.
3. Compute $C_0 = \mathcal{E}_K(M)$, $C_1 = g^s$, and $tag_c = H_2(C_0, C_1) \in \mathbb{Z}_p$.
4. Compute $C_2 = (H_1(ID)u^{tag_c})^s$.
5. Output a ciphertext $CT = (C_0, C_1, C_2) \in \{0, 1\}^{|M|} \times \mathbb{G}^2$.

Decrypt(PP, CT, sk_{ID}): To decrypt a ciphertext $CT = (C_0, C_1, C_2)$ using a private key $sk_{ID} = (d_0, d_1, d_2)$ for ID, the decryption algorithm does as follows:

1. Compute $tag_c = H_2(C_0, C_1)$ and $tag_k = H_2(d_0, d_1)$.
2. Check if $e(H_1(ID)u^{tag_c}, C_1) \stackrel{?}{=} e(C_2, g)$.
3. If the equality above fails, output \perp .
4. Otherwise, check if $tag_c \stackrel{?}{=} tag_k$.
5. If the equality above holds, output \perp .

6. Otherwise, compute a key

$$K = e(d_0, C_1) \cdot \left(\frac{e(C_2, d_1)}{e(d_2, C_1)} \right)^{\frac{-1}{\text{tag}_c - \text{tag}_k}}.$$

7. Output a message $M = \mathcal{D}_K(C_0)$.

Remark. The efficiency of the IBE system above is almost the same as that in the previous section. Notice that the KEM part in a ciphertext is not expanded and the DEM part $C_0 = \mathcal{E}_K(M)$ is also hashed and embedded into the ciphertext element C_3 . As a result, we can check the consistency of ciphertext elements including the DEM part and therefore avoid relying on an authenticated encryption scheme with the help of a secure message authentication code (MAC). In practice, a one-time symmetric-key encryption scheme $\mathcal{SK}\mathcal{E}$ with key-space $\mathcal{K} \in \{0, 1\}^k$ can be implemented by AES with a counter mode, and a real symmetric key for \mathcal{E} can be obtained via a key-derivation function [27] that maps an element from \mathbb{G}_T into $2k$ -bit strings.

4.2 Security

Theorem 2. *Let H_1 and H_2 be modeled as random oracles. Suppose the (t', ε') -DBDH assumption holds in \mathbb{G} and the one-time symmetric-key encryption scheme $\mathcal{SK}\mathcal{E}$ is (t'', ε'') -secure against passive attacks. Then our IBE system is $(t, \varepsilon, q_K, q_D)$ -IND-ID-CCA secure, where*

$$\begin{aligned} \varepsilon &\leq \left(1 - \left(\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p} \right) \right) \cdot (\varepsilon' + \varepsilon''), \\ t &\geq t' + t'' - \mathcal{O}(q_K \cdot t_e) - \mathcal{O}(q_D \cdot (t_p + t_{\text{symD}})). \end{aligned}$$

Here, t_e is the cost of an exponentiation in \mathbb{G} , t_p is the cost of a pairing computation in \mathbb{G} , and t_{symD} is the cost of symmetric-key decryption in the $\mathcal{SK}\mathcal{E}$.

Proof. The proof of Theorem 2 is similar to that of Theorem 1. For clarity, we reconstruct the entire proof by creating a sequence of hybrid games. If necessary, we will adapt several notations that appeared in the proof of Theorem 1 without explicit explanation.

Let \mathcal{A} be an adversary on the chosen ciphertext security of our IBE system above. We will consider two games, **Game 0** and **Game 1**, each game interacting with \mathcal{A} . Let X_i (for $i = 0, 1$) be the event that in **Game i**, \mathcal{A} wins the game.

Game 0. The game is a real attack game of chosen ciphertext security, so that (for a security parameter k) we have

$$|\Pr[X_0] - 1/2| = \mathbf{Adv}_{\mathcal{IBE}, \mathcal{A}}^{\text{CCA}}(k). \quad (3)$$

Game 1. The game is the same as Game 0, except that the value K^* used for a symmetric key in CT^* is replaced by a random value $K \in \mathbb{G}_T$. Unless the events $\text{abort}_1, \dots, \text{abort}_6$ (defined in the proof of Theorem 1) occur in **Game 1**, we have

$$|\Pr[X_1] - \Pr[X_0]| = \left(1 - \left(\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p} \right) \right) \cdot \mathbf{Adv}_{\mathbb{G}, \mathcal{B}_1}^{\text{DBDH}}(k), \quad (4)$$

where \mathcal{B}_1 is an algorithm whose goal is to solve a DBDH problem.

The proof of the above relation is almost the same as that of Theorem 1. When \mathcal{B}_1 is given (g, g^a, g^b, g^c, T) as an input, we describe how CT^* is computed: when \mathcal{A} outputs two messages $M_0, M_1 \in \{0, 1\}^*$ of the same length and an identity ID^* , \mathcal{B}_1 picks a random bit $\sigma \in \{0, 1\}$. Let $\langle \text{ID}^*, \gamma^*, \pi^*, H_1(\text{ID}^*) \rangle$ be the tuple in the H_1^{list} regarding ID^* . \mathcal{B}_1 sets $C_0^* = \mathcal{E}_T(M_\sigma)$, $C_1^* = g^c$, and $H_2(C_0^*, C_1^*) = \gamma^*$. If the tuple $\langle C_0^*, C_1^*, \gamma_j \rangle$ are already in the H_2^{list} and $\gamma_j \neq \gamma^*$, then \mathcal{B}_1 aborts. (In Game 1, the event has already been taken into consideration under the event abort4.) Otherwise, the challenge ciphertext is generated as $\text{CT}^* = (C_0^*, C_1^*, C_2^*) = (\mathcal{E}_T(M_\sigma), g^c, (g^c)^{\pi^* + \delta\gamma^*})$. Other slight differences reside in handling decryption and H_2 queries. Answering decryption queries needs to run \mathcal{D} of $\text{SK}\mathcal{E}$, and inputs (W_i, Q_i) to H_2 queries are in either \mathbb{G}^2 or $\{0, 1\}^* \times \mathbb{G}$ (instead of \mathbb{G}^2 or $\mathbb{G}_T \times \mathbb{G}$). However, the way of answering H_2 queries is the same as in the proof of Theorem 1. Therefore, the probability that appeared in (4) is the same as that in Theorem 1.

Finally, in **Game 1** we have the following relation that directly comes from the definition of ciphertext indistinguishability for $\text{SK}\mathcal{E}$ unless the events abort1, ..., abort6 (defined in the proof of Theorem 1) occur in **Game 1**.

$$|\Pr[X_1] - 1/2| = \left(1 - \left(\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}\right)\right) \cdot \text{Adv}_{\text{SK}\mathcal{E}, \mathcal{B}_2}^{\text{OT-IND}}(k), \quad (5)$$

where \mathcal{B}_2 is an algorithm whose goal is to break $\text{SK}\mathcal{E}$.

One thing we want to clarify is that \mathcal{B}_2 does not need to deal with any decryption query on the one-time symmetric-key encryption scheme $\text{SK}\mathcal{E}$. In **Game 1**, \mathcal{B}_2 relays the two messages $M_0, M_1 \in \{0, 1\}^*$ to its challenger and is given a challenge ciphertext $\mathcal{E}_{K^*}(M_\sigma)$ for a random key $K^* \in \mathbb{G}_T$. \mathcal{B}_2 then reconstructs its challenge ciphertext CT^* as explained above and gives it to \mathcal{A} . Whenever \mathcal{A} requests any decryption query on CT_i , \mathcal{B}_2 can use private keys (generated by \mathcal{B}_2) to perform normal decryption. The only troublesome queries happen when \mathcal{A} issues decryption queries on valid $\text{CT}_i = (C_{0,i}, C_{1,i}^*, C_{2,i})$, in which case \mathcal{B}_2 has to use the *unknown* symmetric-key K^* to retrieve a message. Fortunately, those troublesome ones can be addressed in Query Phase 2 of Theorem 1, where \mathcal{B}_2 can use such queries to solve the DBDH problem unless the event abort5 occurs.

Analysis. It is easy to see that time complexity is obviously achieved as argued in Theorem 2. Throughout the simulation, we assume that Cases 3 and 4 described in Query Phase 2 of Theorem 1 do not happen (which would rather increase our success probability to solve the DBDH problem). Putting the results of all relations (3), (4), and (5) above together, we gain a bound on the advantage of the adversary breaking the CCA security as follows:

$$\text{Adv}_{\text{IBE}, \mathcal{A}}^{\text{CCA}}(k) \leq \left(1 - \left(\frac{q_{H_2}(q_K + q_D)}{p} + \frac{q_{H_2}}{p} + \frac{3q_D}{p}\right)\right) \cdot (\text{Adv}_{\mathbb{G}, \mathcal{B}_1}^{\text{DBDH}}(k) + \text{Adv}_{\text{SK}\mathcal{E}, \mathcal{B}_2}^{\text{OT-IND}}(k)),$$

which concludes the proof of Theorem 2. ■

5 Comparison to previous IBE systems

In this section we compare our IBE system with the previous practical IBE systems such as BF [15], SK [45, 24, 25], and BB_1 [10] in terms of security and efficiency. For more detailed comparison between the three previous ones, we refer to Boyen's work [19]. Following Bellare and Rogaway [6, 41], we estimate the number of (random oracle) hash queries as $q_H = 2^{50}$ and the number of private key queries as $q_K = 2^{25}$. For a fair comparison we consider the decisional type of security assumptions in each system, so that BF and BB_1 systems are based on the Decisional BDH assumption and the SK system relies on the q -Decisional

Table 1: Security assumptions and reductions for IBE systems

	Assumption	Security reduction	
		Asymptotic bound	Concrete loss [♠]
BF	DBDH	q_H^2	$> 2^{50}$
BB ₁ [♡]	DBDH	q_H	2^{50}
SK	q -DBDHI	q_H^2	$> 2^{50}$
Ours	DBDH	1	1

q_H : the number of (random-oracle) hash queries; q_K : the number of private key queries;
[♠]: estimated with $q_H = 2^{50}$ and $q_K = 2^{25}$; $q \approx q_H + q_K$;
[♡]: we borrow CCA-secure BB₁ system from [19];

Table 2: Representation sizes and estimated calculation times for various algebraic operations

	Representation sizes (bits)				Relative timings								
	\mathbb{Z}_p	\mathbb{G}	$\widehat{\mathbb{G}}$	\mathbb{G}_T	\mathbb{G}		$\widehat{\mathbb{G}}$			\mathbb{G}_T			
					E_f^\clubsuit	E^\diamond	E_f	E	H^\heartsuit	E_f	E	P^b	P_r^\spadesuit
SS / 80	160	512	512	1024	2	10	2	10	10	2	10	100	120
MNT / 80	160	171	1026	1026	0.2	1	8	40	40	2	10	100	120
MNT / 128	256	512	3072	3072	3	15	100	500	500	30	150	1500	1800

[♣]: fix-base exponentiation; [◇]: general exponentiation; [♡]: hashing; ^b: single pairing; [♠]: ration of pairings;

Bilinear Diffie-Hellman Inversion (DBDHI) assumption² [10] for $q \approx q_H + q_K$. We also refer to [30] for correcting a flawed security analysis of BF system. Table 1 presents the comparison result with respect to security assumptions and reductions, which was also addressed by [19, 41]. The ‘asymptotic bound’ in the security reduction means that the advantage of breaking the CCA security of an IBE system is larger than that of solving a security assumption in comparable time, by a factor of each bound. In other words, the larger the bound is, the bigger the security loss (i.e., gap) is between an IBE system and a security assumption. In Table 1, a concrete bound at each IBE system is estimated when considering the reasonable number of adversarial queries q_H and q_K as 2^{50} and 2^{25} , respectively. The respective bound tells us that, roughly speaking,

$$\mathbf{Adv}_{\mathcal{IBE}, \mathcal{A}}^{\text{CCA}} \leq (\text{bound}) \cdot \mathbf{Adv}_{\mathcal{B}}^{\text{Assumption}} \quad (6)$$

for algorithms \mathcal{A} and \mathcal{B} . When the bound is quite large, we have to choose a larger security parameter k for a security assumption so that we can make $(\text{bound}) \cdot \mathbf{Adv}_{\mathcal{B}}^{\text{Assumption}}$ small and consequently $\mathbf{Adv}_{\mathcal{IBE}, \mathcal{A}}^{\text{CCA}}$ small enough at a desired security level. This is the reason why we have to choose a larger system security parameter than an idealized security level when a large security loss arises at reduction. In contrast to the BF, SK, and BB₁ systems, ours has a *tight* security reduction to the standard DBDH assumption and thus we can say that our IBE system is as secure as the DBDH assumption. We notice that security of the previous three IBE systems as well as ours is all proven in the random oracle model.

²It is defined from the problem: given $(g, g^x, g^{x^2}, \dots, g^{x^q}, T)$, decide whether $T = e(g, g)^{1/x}$ or T is random in \mathbb{G}_T .

Table 3: Efficiency comparison between CCA-secure IBE systems for SS curves at 80-bit security level (not considering security loss)

	Curves / security level	Overheads (bits)		Relative computational costs		
		Public params.	Ciphertext [♠]	Key extraction	Encryption	Decryption
BF	SS / 80	1024	672	20	114	100
BB ₁	SS / 80	2560	1184	4	8	124
SK	SS / 80	2048	672	2	6	106
Ours	SS / 80	2048	1024	28	26	130

♠: considering only KEM part;

When assuming the interactive version of the Gap-BDH assumption³, BF and BB₁ systems can be modified into their respective KEMs [43, 19] that allow for shorter size of ciphertexts and the asymptotic bound for BF-KEM is improved to q_K . However, the Gap-BDH assumption has been perceived as being a non-standard one, and we have no way of comparing it with the DBDH assumption in a fair manner. Also, their corresponding DEMs need authenticated symmetric encryption, which causes a MAC tag to be included into a ciphertext. Indeed, requiring such an additional tag weakens the merit of the shorter ciphertexts. For these reasons, we do not consider their KEMs in our efficiency comparison.

Based on the result of Table 1, we give an efficiency comparison between the previous IBE systems and ours. We consider 80-bit security as a desired security level of IBE systems. As previously mentioned, BF, SK, and BB₁ systems all have concrete security loss of at least 2^{50} so that they must have a larger system security parameter than 80 bits. Obviously, it will be unfair to straightforwardly compare ours with the previous systems at the same security level. However, as a warm-up case, we first give a comparison result when instantiated in supersingular (SS) curves at an 80-bit security level. We notice that our comparison is based on Boyen’s work [19] that investigates relatively estimated calculation times for various operations and representation sizes for group elements. Table 2 presents the result (see Table 7 and 8 in [19] for more details) when considering SS curves at the 80-bit security level and MNT curves at security levels 80 and 128. The numerical results of our comparison are given in Table 3. In doing so, we estimate that the encryption algorithm in our system requires three fixed-base exponentiations, one hashing $H_1(\text{ID})$ for an identity ID, and one general exponentiation involving $H_1(\text{ID})^s$, which makes relative encryption cost 26. Upon decryption, such hashing and general exponentiation do not need to be counted as a decryptor is able to compute $H_1(\text{ID})$ for *its* identity ID beforehand. As discussed in Section 3.1, the decryption algorithm then needs to compute five fixed-base exponentiations plus 1.2 pairings. Table 3 demonstrates that our system is comparable to the other IBE systems in terms of all efficiency respects, even though the relative computational costs are slightly more expensive than others. We again emphasize that the comparison above does not take into account the security losses caused by the security reductions on Table 1.

For a fairer comparison, we try to compensate for such security losses by boosting the security parameter of the underlying assumptions. There is no general rule of such compensation, but we might be able to use conjectures that were made by Bellare and Rogaway [7] for advantage functions of various block ciphers. For instance, the advantage of DES with 128-bit keys was conjectured as (roughly speaking) $\text{Adv}_{\text{AES}}^{\text{CPA}} \leq c/2^{128}$ for some constant c . A similar approach can be made for advantages of IBE systems, so that we

³It is defined by the following problem: given (g, g^a, g^b, g^c, O) , output $e(g, g)^{abc}$. Here, the O is a decision oracle that takes as inputs four arbitrary elements (g^x, g^y, g^z, T) in $\mathbb{G}^3 \times \mathbb{G}_T$, outputs 1 if $T = e(g, g)^{xyz}$ and otherwise 0.

Table 4: Efficiency comparison between CCA-secure IBE systems at corrected 80-bit security level

	Curves / security level	Overheads (bits)		Relative computational costs		
		Public params.	Ciphertext [♠]	Key extraction	Encryption	Decryption
BF	MNT / 128	1024	768	1000	2006	1503
BB ₁	MNT / 128	4608	1280	200	39	1833
SK	MNT / 128	4096	768	100	36	1536
Ours	SS / 80	2048	1024	28	26	130

♠: considering only KEM part;

want to make $\text{Adv}_{\text{IBE}, \mathcal{A}}^{\text{CCA}} \leq c/2^{80}$ at the 80-bit security level. In that case, equation (6) tells us that we have to make $\text{Adv}_{\mathcal{B}}^{\text{Assumption}} \leq c/2^{130}$ when considering that the security loss is bounded under 2^{50} . For simplicity, we assume that the reduction bounds in both BF and SK systems are 2^{50} (although they are much larger than it). Under these assumptions, the actual security parameter must be of 130 bits in size (approximately) to gain the real system security of an IBE system at the desired 80-bit security level. To accomplish this, we consider that the BF, BB₁, and SK systems are instantiated in MNT curves at the 128-bit security level, whereas ours is based on SS curves at the 80-bit security level as before. Table 4 shows the efficiency comparison result between CCA-secure IBE systems. We can see that the computational cost in ours becomes superior to the other systems. In particular, decryption time becomes at least 11 times faster than the others and encryption time becomes roughly 77 times faster than the BF system.

6 Discussion

6.1 A New Public Key Signature Scheme

According to Naor’s observation [15], any IBE system can be converted into a secure (public key) signature scheme under the same assumptions. Naturally, we can have a signature scheme based on our IBE system, the security of which is proven under the DBDH assumption in the random oracle model. However, by using the private key structure of the IBE system, we can derive a new signature scheme whose security relies on the Computational Diffie-Hellman (CDH) assumption. Similar derivations have already been used for obtaining previous signature schemes such as BLS [17], Waters [48], and Boyen and Boneh [11]. One favorable feature of our derived signature scheme is that ours can have a *tight* security reduction to the CDH assumption. Prior to our work, BLS signature can be modified into a scheme that has a tighter security reduction to the CDH assumption with the help of the Katz-Wang technique [39]. Our signature scheme gives an alternative method for achieving such a tight security reduction, which is different from the Katz-Wang technique. Another favorable feature is that ours is secure in the sense of *strong* unforgeability. Informally, the ‘strong’ means that an adversary cannot even generate a new signature for a previously-signed message. This notion is stronger than the standard notion of GMR unforgeability [36] and can be used for providing CCA security [22, 13] of various encryption schemes.

Construction. We describe our signature scheme for completeness.

Setup(k): Given a security parameter $k \in \mathbb{Z}^+$, the setup algorithm runs $\mathcal{G}(k)$ to obtain a tuple $(p, \mathbb{G}, \mathbb{G}_T, e)$. The algorithm selects a random generator $g \in \mathbb{G}$, a random group element $u \in \mathbb{G}$, and a random exponent $\alpha \in \mathbb{Z}_p$. The algorithm sets $A = e(g, g)^\alpha$ and chooses two cryptographic hash functions $H_1 : \{0, 1\}^* \rightarrow \mathbb{G}$

and $H_2 : \{0, 1\}^* \rightarrow \mathbb{Z}_p$. The public key PK (with the description of $(p, \mathbb{G}, \mathbb{G}_T, e)$) and the secret key sk are generated as

$$\text{PK} = (g, u, A, H_1, H_2), \quad \text{sk} = \alpha.$$

Sign(m, sk, PK): To sign a message $m \in \{0, 1\}^*$, the signing algorithm does the following:

1. Choose a random $r \in \mathbb{Z}_p$.
2. Compute $\sigma_1 = g^\alpha u^r$, $\sigma_2 = g^r$, and $\text{tag} = H_2(\sigma_1, \sigma_2) \in \mathbb{Z}_p$.
3. Compute $\sigma_3 = (H_1(m)u^{\text{tag}})^r$.
4. Output a signature $\sigma = (\sigma_1, \sigma_2, \sigma_3) \in \mathbb{G}^3$.

Verify(PK, m, σ): To verify a signature $\sigma = (\sigma_1, \sigma_2, \sigma_3)$ on a message m , the verification algorithm does the following:

1. Compute $\text{tag} = H_2(\sigma_1, \sigma_2)$.
2. Output accept if the following two equations hold:

$$e(\sigma_1, g) \stackrel{?}{=} A \cdot e(u, \sigma_2), \quad e(\sigma_3, g) \stackrel{?}{=} e(H_1(m)u^{\text{tag}}, \sigma_2).$$

If either check fails, output reject.

The number of pairings in the verification algorithm is four, but it can be reduced to two by the similar calculation to the one as in the decryption algorithm of the IBE system. To do this, the verification algorithm picks a random $s \in \mathbb{Z}_p$ and checks if the following equation holds:

$$e(\sigma_1 \cdot \sigma_3^s, g) \stackrel{?}{=} A \cdot e(u \cdot (H_1(m)u^{\text{tag}})^s, \sigma_2).$$

We can prove the security of our signature scheme. The proof of Theorem 3 will be given in Appendix I, along with definitions of public key signature and strong unforgeability.

Theorem 3. *Let H_1 and H_2 be modeled as random oracles. Suppose the (t', ϵ') -CDH assumption holds in \mathbb{G} . Then our signature scheme is (t, ϵ, q_S) -secure in the sense of strong unforgeability under adaptive chosen message attacks, where*

$$\epsilon = \left(1 - \left(\frac{q_{H_2} q_S}{p} + \frac{2q_{H_2}}{p}\right)\right) \cdot \epsilon', \quad t \approx t' - \mathcal{O}(q_S \cdot t_e).$$

Here, t_e is the cost of an exponentiation in \mathbb{G} .

6.2 On Extension for Hierarchical IBE system

In a hierarchical IBE (HIBE) system [38, 34], a user's identity ID can be hierarchically scalable by delegating a private key sk_{ID} to lower-level identities. For instance, a user with identity ID_1 can generate a private key $\text{sk}_{\text{ID}'}$ for a lower-level identity $\text{ID}' = (\text{ID}_1, \text{ID}_2)$ using its own private key sk_{ID_1} . The reverse of key generation (i.e., from lower level to upper level) is not possible. This is called the 'delegation mechanism'. Using it, an HIBE system can be used for several applications including forward-secure encryption [21] and

conversion for public key broadcast encryption [28]. In a security analysis for HIBE, an adversary is given the capability to request either private keys generated by a key generation center or ones delegated from upper-level identities of its choice.

One may wonder if our IBE system can be extended for supporting hierarchical identities. As far as we know, the answer is no. Since the private key structure of our system has similarity to that of Waters' tag-based dual system encryption [49], it may seem possible that a similar extension method can be applied to ours. However, the problem occurs because of the 'locked' tag values associated with upper-level identities. In the security analysis of the resulting HIBE system, an adversary requests a private key for an identity $ID = (ID_1, \dots, ID_\ell)$. In order to generate a private key sk_{ID} , we have to use one of the hidden values⁴ that are embedded into $\{H_i(ID_i)\}$ for $i = 1, \dots, \ell$. Assume we use a hidden value in $H_k(ID_k)$ for $k \leq \ell$. In that case, the tag values corresponding to j for $j < k$ are chosen at random and mapped to H_2 -query outputs in an appropriate sense. However, those random tag values are locked and cannot be changed into other different values. The adversary can still query private keys for upper-level identities, e.g., $ID' = (ID_1, \dots, ID_{k-1})$, in which $sk_{ID'}$ should be generated using those locked tags. Unfortunately, such a private key cannot be generated. One solution would be to use hidden values for each level of hierarchy, but instead it can reveal all hidden tag values that must be secretly reserved for challenge ciphertext. We leave it as an open problem to build a hierarchical version from our IBE system.

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⁴Those are γ_i values that appear in the H_1^{list} in the proof of Theorem 1 and 2.

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A Public Key Signature

A.1 Definition of Public Key Signature

A (public key) signature scheme is a tuple of three algorithms $\mathcal{PKS} = (\mathbf{Setup}, \mathbf{Sign}, \mathbf{Verify})$ over a message space \mathcal{M} .

Setup(k): takes as input a security parameter k and outputs a public key PK and a secret key sk.

Sign(sk, PK, m): takes a secret key sk, the public key PK, and a message $m \in \mathcal{M}$ as input and returns a signature σ .

Verify(PK, m , σ): takes a public key PK, a message m , and a signature σ as input and returns accept or reject.

We make the standard correctness requirement: for all (PK, sk) output by **Setup** and all $m \in \mathcal{M}$, we have $\mathbf{Verify}(\text{PK}, m, \mathbf{Sign}(\text{sk}, \text{PK}, m)) = \text{accept}$.

A.2 Security: strong unforgeability

We give the definition of *strong* unforgeability under adaptive chosen message attacks [11]. This security notion states that an adversary cannot even generate a new signature for a previously-signed message. The security is defined via an interaction between an adversary \mathcal{A} (i.e., a forger against a signature scheme) and a challenger \mathcal{C} :

Setup: \mathcal{C} runs the setup algorithm to obtain a pair (PK, sk). It gives PK to \mathcal{A} and keeps sk secret.

Query Phase: \mathcal{A} issues signature queries on messages $\{m_i\}$ that can be adaptively chosen, depending on previous signatures and messages. Using sk, \mathcal{C} runs the signing algorithm for each message and returns a resulting signature as a response.

Output: \mathcal{A} outputs a valid signature σ^* and a message m^* such that: (1) $\mathbf{Verify}(\text{PK}, m^*, \sigma^*) = \text{accept}$, and (2) $(m^*, \sigma^*) \notin \Sigma$, where Σ is the set of pairs (m_i, σ_i) such that σ_i was the response to a signature query.

The advantage of an adversary \mathcal{A} that breaks the strong unforgeability of a signature scheme \mathcal{PKS} is defined as

$$\mathbf{Adv}_{\mathcal{PKS}, \mathcal{A}}^{\text{sup}}(k) = \Pr \left[\mathcal{A} \rightarrow (m^*, \sigma^*) : \mathbf{Verify}(\text{PK}, m^*, \sigma^*) = \text{accept} \wedge (m^*, \sigma^*) \notin \Sigma \right].$$

Definition 4. We say that signature scheme \mathcal{PKS} is (t, ϵ, q_S) -secure in the sense of strong unforgeability if no adversary that runs in time at most t and issues at most q_S signature queries breaks the strong unforgeability with advantage at most ϵ .

A.3 CDH assumption

The Computational Diffie-Hellman (CDH) Problem: The well-known CDH problem is defined as follows: given $(g, g^a, g^b) \in \mathbb{G}^3$ as input, output g^{ab} . We say that an algorithm \mathcal{A} has advantage $\mathbf{Adv}_{\mathbb{G}, \mathcal{A}}^{\text{CDH}} = \epsilon$ in solving the CDH problem in \mathbb{G} if $\mathbf{Adv}_{\mathbb{G}, \mathcal{A}}^{\text{CDH}} = \Pr[\mathcal{A}(g, g^a, g^b) = g^{ab}]$, where the probability is taken over the random choice of $a, b \in \mathbb{Z}_p$ and the random bits used by \mathcal{A} .

Definition 5. We say that the (t, ϵ) -CDH assumption holds in \mathbb{G} if for any polynomial time adversary \mathcal{A} that runs in time at most t in solving the CDH problem in \mathbb{G} , the advantage $\mathbf{Adv}_{\mathbb{G}, \mathcal{A}}^{\text{CDH}}$ is negligible.

A.4 Proof of Theorem 3

Proof. Suppose that there exists an adversary \mathcal{A} which can break the strong unforgeability of our signature scheme. We can then build an algorithm \mathcal{B} which uses \mathcal{A} to solve a CDH problem in \mathbb{G} . On input (g, g^a, g^b) , \mathcal{B} tries to output g^{ab} . \mathcal{B} interacts with \mathcal{A} as follows.

Setup \mathcal{B} selects a random element $\delta \in \mathbb{Z}_p$ and sets $u = g^{-a}g^\delta$ and $A = e(g^a, g^b)$. Note that $\alpha = ab \in \mathbb{Z}_p$, which is unknown to \mathcal{B} . Then \mathcal{A} is given the public key $\text{PK} = (g, u, A, H_1, H_2)$, where H_1 and H_2 are modeled as random oracles.

Query Phase \mathcal{A} issues $\{H_i\}_{i=1,2}$ and signature queries. \mathcal{B} responds as follows:

H_1 queries: To respond to H_1 queries, \mathcal{B} maintains a list of tuples $\langle m_i, \gamma_i, \pi_i, H_1(m_i) \rangle$ as explained below. We refer to this list as the H_1^{list} . When \mathcal{B} is given a message $m_i \in \{0, 1\}^*$ as an input to H_1 , \mathcal{B} first scans through the H_1^{list} to see if the input m_i appears in a tuple $\langle m_i, \gamma_i, \pi_i, H_1(m_i) \rangle$. If it does, \mathcal{B} responds with $H_1(m_i)$. Otherwise, \mathcal{B} picks two random exponents $\gamma_i, \pi_i \in \mathbb{Z}_p$ and sets $H_1(m_i) = (g^a)^{\gamma_i} g^{\pi_i} \in \mathbb{G}$. \mathcal{B} adds the new tuple $\langle m_i, \gamma_i, \pi_i, H_1(m_i) \rangle$ to the H_1^{list} and responds with $H_1(m_i)$. Recall that the values $\{\gamma_i\}$ are information-theoretically hidden to \mathcal{A} 's view.

H_2 queries: To respond to H_2 queries, \mathcal{B} maintains a list of tuples $\langle W_i, Q_i, \mu_i \rangle$ as explained below. We refer to this list as the H_2^{list} . When \mathcal{B} is given values $(W_i, Q_i) \in \mathbb{G}^2$ as an input to H_2 , \mathcal{B} first scans through the H_2^{list} to see if the input (W_i, Q_i) appears in a tuple $\langle W_i, Q_i, \mu_i \rangle$. If it does, \mathcal{B} responds with $H_2(W_i, Q_i) = \mu_i$. Otherwise, \mathcal{B} picks a random exponent $\mu_i \in \mathbb{Z}_p$ and sets $H_2(W_i, Q_i) = \mu_i$. \mathcal{B} adds the new tuple $\langle W_i, Q_i, \mu_i \rangle$ to the H_2^{list} and responds with $H_2(W_i, Q_i)$.

Signature queries: When \mathcal{B} is given a message $m_i \in \{0, 1\}^*$ as an input to a signature query, \mathcal{B} selects a random exponent $r \in \mathbb{Z}_p$ and (implicitly) sets $\tilde{r} = b + r \in \mathbb{Z}_p$. \mathcal{B} computes $\sigma_{1,i} = (g^a)^{-r} (g^b)^\delta g^{\delta r}$ and $\sigma_{2,i} = g^b g^r$. The validity of those elements can be verified as follows:

$$\sigma_{1,i} = (g^a)^{-r} (g^b)^\delta g^{\delta r} = g^{ab} (g^{-a} g^\delta)^{b+r} = g^\alpha u^{\tilde{r}}, \quad \sigma_{2,i} = g^b g^r = g^{\tilde{r}}.$$

Next, \mathcal{B} refers to the H_1^{list} to find out the tuple $\langle m_i, \gamma_i, \pi_i, H_1(m_i) \rangle$. (If no tuple exists, \mathcal{B} can run the H_1 -query process before replying to the signature query.) At this moment, \mathcal{B} 's goal is to set $H_2(\sigma_{1,i}, \sigma_{2,i}) = \gamma_i$. Thus, if there is a tuple $\langle \sigma_{1,i}, \sigma_{2,i}, \gamma_i \rangle$ in the H_2^{list} , \mathcal{B} can continue the signature query process. However, there could be the case where \mathcal{A} already issued $(\sigma_{1,i}, \sigma_{2,i})$ to the H_2 query and set $H_2(\sigma_{1,i}, \sigma_{2,i}) = \mu_i \neq \gamma_i$, in which case \mathcal{B} cannot generate the element $\sigma_{3,i}$. To see whether there already exists the tuple $\langle \sigma_{1,i}, \sigma_{2,i}, \mu_i \rangle$ such that $\mu_i \neq \gamma_i$, \mathcal{B} refers to the H_2^{list} .

[Case 1.] If the tuple exists, \mathcal{B} aborts. (We refer to this event as abort1.) From the proof of Theorem 1, we know that the probability that the event abort1 happens during the simulation is at most $q_S q_{H_2} / p$.

[Case 2.] If the tuple does not exist, \mathcal{B} sets $H_2(\sigma_{1,i}, \sigma_{2,i}) = \gamma_i$ (where γ_i is from the tuple in the H_1^{list} above) and adds the tuple $\langle \sigma_{1,i}, \sigma_{2,i}, \gamma_i \rangle$ to the H_2^{list} . \mathcal{B} generates the element $\sigma_{3,i}$, using $H_2(\sigma_{1,i}, \sigma_{2,i}) = \gamma_i$, as $\sigma_{3,i} = (g^b)^{\pi_i + \gamma_i \delta} g^{(\pi_i + \gamma_i \delta)r}$. The validity of $\sigma_{3,i}$ can be verified as follows:

$$\sigma_{3,i} = (g^b)^{\pi_i + \gamma_i \delta} g^{(\pi_i + \gamma_i \delta)r} = ((g^a)^{\gamma_i} g^{\pi_i} \cdot (g^{-a+\delta})^{\gamma_i})^{b+r} = (H_1(m_i) u^{H_2(\sigma_{1,i}, \sigma_{2,i})})^{\tilde{r}}.$$

Then, \mathcal{B} responds with a signature $\sigma_i = (\sigma_{1,i}, \sigma_{2,i}, \sigma_{3,i})$ for the requested message m_i .

Output At this moment \mathcal{A} outputs a valid forgery (m^*, σ^*) , where $\sigma^* = (\sigma_1^*, \sigma_2^*, \sigma_3^*)$. There are two possible cases:

[Case 1.] m^* is not queried during the signature queries. \mathcal{B} refers to the H_1^{list} and finds the tuple $\langle m^*, \gamma^*, \pi^*, H_1(m^*) \rangle$ and it also refers to the H_2^{list} to find the tuple $\langle \sigma_1^*, \sigma_2^*, \mu^* \rangle$. If $\gamma^* = \mu^*$, then

\mathcal{B} aborts. (We refer to this event as abort2.) The probability that the event abort2 happens during the simulation is at most q_{H_2}/p , because the exponent γ^* (regarding m^*) is predetermined so that each output corresponding to a H_2 query can map to the γ^* with probability at most $1/p$. If $\gamma^* \neq \mu^*$, then \mathcal{B} has that $H_2(\sigma_1^*, \sigma_2^*) = \mu^* \neq \gamma^*$. From the two equality checks in the verification algorithm, \mathcal{B} has that for some unknown exponent $\hat{r} \in \mathbb{Z}_p$ such that $\sigma_2^* = g^{\hat{r}}$:

$$\sigma_1^* = g^\alpha \cdot u^{\hat{r}}, \quad \sigma_2^* = g^{\hat{r}}, \quad \sigma_3^* = (H_1(m^*)u^{\mu^*})^{\hat{r}}.$$

We know that $H_1(m^*) = (g^a)^\gamma g^{\pi^*}$ and $u = g^{-a}g^\delta$, which leads to $\sigma_3^* = (g^a)^{(\gamma^* - \mu^*)\hat{r}} g^{(\pi^* + \delta)\hat{r}}$. Thus, \mathcal{B} can obtain the value $g^{\hat{r}}$ by computing $(\sigma_3^*/(\sigma_1^*)^{\pi^* + \delta})^{(\gamma^* - \mu^*)^{-1}}$. Next, we know that $\sigma_1^* = g^{ab} \cdot (g^{-a}g^\delta)^{\hat{r}}$. It follows that \mathcal{B} can obtain g^{ab} as $\sigma_1^* \cdot g^{\hat{r}}/(\sigma_1^*)^\delta$.

[Case 2.] m^* is one of queried messages. Say $m^* = m_t$ for some $t \in \{1, \dots, q_S\}$ and the corresponding signature (that was generated in Query Phase) is $\sigma_t = (\sigma_{1,t}, \sigma_{2,t}, \sigma_{3,t})$. Again, \mathcal{B} refers to the H_1^{list} and finds the tuple $\langle m_t, \gamma_t, \pi_t, H_1(m_t) \rangle$ and also it refers to the H_2^{list} to find the two tuples $\langle \sigma_1^*, \sigma_2^*, \mu^* \rangle$ and $\langle \sigma_{1,t}, \sigma_{2,t}, \gamma_t \rangle$. Notice that γ_t regarding m_t was used to generate the signature σ_t . In this case, it should be the case that $\sigma^* \neq \sigma_t$. We further consider all seven different cases:

[Case 2.1.] $\sigma_1^* \neq \sigma_{1,t}, \sigma_2^* \neq \sigma_{2,t}, \sigma_3^* \neq \sigma_{3,t}$. If $\mu^* = \gamma_t$, \mathcal{B} aborts. (We refer to this event as abort3.) The probability that the event abort3 happens during the simulation is at most q_{H_2}/p as in Case 1. Otherwise, \mathcal{B} can compute g^{ab} as in Case 1.

[Case 2.2.] $\sigma_1^* \neq \sigma_{1,t}, \sigma_2^* = \sigma_{2,t}, \sigma_3^* = \sigma_{3,t}$. In this case, we know from the first equality check in the verification algorithm that σ_1^* should be of the form $g^\alpha u^{\tilde{r}}$ for some exponent $\tilde{r} \in \mathbb{Z}_p$ such that $\sigma_2^* = g^{\tilde{r}}$. Also, we had that $\sigma_{1,t} = g^\alpha u^{\tilde{r}}$ so that it should be that $\sigma_1^* = \sigma_{1,t}$, which is a contradiction.

[Case 2.3.] $\sigma_1^* = \sigma_{1,t}, \sigma_2^* \neq \sigma_{2,t}, \sigma_3^* = \sigma_{3,t}$. In this case, we know from the first equality check in the verification algorithm that σ_1^* should be of the form $g^\alpha u^{r''}$ for some exponent $r'' \in \mathbb{Z}_p$ such that $\sigma_2^* = g^{r''}$. Also, we had that $\sigma_{1,t} = g^\alpha u^{\tilde{r}}$ for some exponent $\tilde{r} \in \mathbb{Z}_p$ such that $\sigma_{2,t} = g^{\tilde{r}}$. Since $\sigma_2^* \neq \sigma_{2,t}$, this means that $r'' \neq \tilde{r}$. Nevertheless, it should be that $g^\alpha u^{r''} = g^\alpha u^{\tilde{r}}$, which is a contradiction.

[Case 2.4.] $\sigma_1^* = \sigma_{1,t}, \sigma_2^* = \sigma_{2,t}, \sigma_3^* \neq \sigma_{3,t}$. In this case, we know that $\mu^* = \gamma_t$. Then, from the second equality check in the verification algorithm, σ_3^* should be of the form $(H_1(m_t)u^{\mu^*})^{\tilde{r}}$ for some exponent $\tilde{r} \in \mathbb{Z}_p$ such that $\sigma_2^* = g^{\tilde{r}}$. Also, we had that $\sigma_{3,t} = (H_1(m_t)u^{\gamma_t})^{\tilde{r}}$. Since $\mu^* = \gamma_t$, it should be that $\sigma_3^* = \sigma_{3,t}$, which is a contradiction.

[Case 2.5.] $\sigma_1^* = \sigma_{1,t}, \sigma_2^* \neq \sigma_{2,t}, \sigma_3^* \neq \sigma_{3,t}$. This cannot happen because of the same reason for Case 2.3.

[Case 2.6.] $\sigma_1^* \neq \sigma_{1,t}, \sigma_2^* = \sigma_{2,t}, \sigma_3^* \neq \sigma_{3,t}$. This cannot happen because of the same reason for Case 2.2.

[Case 2.7.] $\sigma_1^* \neq \sigma_{1,t}, \sigma_2^* \neq \sigma_{2,t}, \sigma_3^* = \sigma_{3,t}$. If $\mu^* = \gamma_t$, we know from the second equality check in the verification algorithm that σ_3^* should be of the form $(H_1(m_t)u^{\mu^*})^{r''}$ for some exponent $r'' \in \mathbb{Z}_p$ such that $\sigma_2^* = g^{r''}$. Also, we had that $\sigma_{3,t} = (H_1(m_t)u^{\gamma_t})^{\tilde{r}}$ for some exponent $\tilde{r} \in \mathbb{Z}_p$ such that $\sigma_{2,t} = g^{\tilde{r}}$. Since $\sigma_2^* \neq \sigma_{2,t}$, this means that $r'' \neq \tilde{r}$. Nevertheless, it should be that $(H_1(m_t)u^{\mu^*})^{r''} = (H_1(m_t)u^{\gamma_t})^{\tilde{r}}$, which is a contradiction. Otherwise, i.e., if $\mu^* \neq \gamma_t$, then \mathcal{B} can compute g^{ab} as in Case 1.

Analysis. The computational time that \mathcal{B} requires is dominated by exponentiations for handling q_S signature queries. Thus, the inequality concerning the computational time can easily be obtained. Next, to analyze

\mathcal{B} 's advantage, we prove the following claim that argues that the probability that \mathcal{B} aborts in the simulation is at most $\frac{q_{H_2}q_S}{p} + \frac{2q_{H_2}}{p}$, which is negligible.

Claim 2: $\Pr[\text{abort}] = \Pr[\text{abort1} \vee \text{abort2} \vee \text{abort3}]$ in the simulation is at most $\frac{q_{H_2}q_S}{p} + \frac{2q_{H_2}}{p}$.

Proof. The proof is similar to that of Claim 1. Analyzing each probability is addressed in the simulation. As all the events that \mathcal{B} aborts are relatively independent, it follows that the probability $\Pr[\text{abort1} \vee \text{abort2} \vee \text{abort3}]$ in the simulation is at most $\frac{q_{H_2}q_S}{p} + \frac{2q_{H_2}}{p}$. \square

Next, we can see that as long as \mathcal{B} does not abort in the simulation, \mathcal{B} provides \mathcal{A} with a perfect simulation whose distribution is identical to the distribution in a real interaction with a signer. This is because (1) the simulation of both H_1 and H_2 oracles are obviously perfect as the output values are chosen by randomly chosen values in \mathbb{G} and \mathbb{Z}_p , respectively, and (2) the simulation of signature oracles are also perfect as each signature on a message is generated with a randomly chosen exponent $r \in \mathbb{Z}_p$ such that $\tilde{r} = b + r$, and (3) the values $\{\gamma_i\}$ in the H_1^{list} are uniformly distributed and information-theoretically hidden from \mathcal{A} 's view until signatures answered by \mathcal{B} are given to \mathcal{A} .

It follows that as long as \mathcal{B} does not abort in the simulation, \mathcal{B} can use \mathcal{A} 's advantage to break the strong unforgeability of our signature scheme straightforwardly. Then, from Claim 2, \mathcal{B} 's success probability is given as follows:

$$\mathbf{Adv}_{\mathbb{G}, \mathcal{B}}^{\text{CDH}}(k) = \left(1 - \left(\frac{q_{H_2}q_S}{p} + \frac{2q_{H_2}}{p}\right)\right) \cdot \mathbf{Adv}_{\mathcal{PKS}, \mathcal{A}}^{\text{uf}}(k),$$

as required. This concludes the proof of Theorem 3. \blacksquare