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A New Leakage-Resilient IBE Scheme in the Relative Leakage Model

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Abstract. We propose the first leakage-resilient Identity-Based Encryption (IBE) scheme with full domain hash structure. Our scheme is leakage-resilient in the relative leakage model and the random oracle model under the decisional bilinear Diffie-Hellman (DBDH) assumption.

Key words: identity based encryption, leakage-resilient, relative leakage, bilinear Diffie-Hellman assumption

1 Introduction

Cryptographic schemes are used to be analyzed in an attack model in which the internal secret states are completely hidden from the adversary/attacker. However several works [12, 13] indicated that the attack model fails to capture many attacks in the real world, since the attacker may obtain some partial information about the secret states via various *key leakage attacks*. Therefore it is urgent to design leakage-resilient cryptographic schemes which remain provably secure in the strengthened attack model which takes *key leakage attacks* into account.

Recently, the research community pay a lot of attention to construct IBE schemes with leakage-resilience. Alwen et al. [1] presented three leakage-resilient IBE schemes from the Gentry IBE [10], the Boneh-Gentry-Hamburg IBE [4], and Gentry-Peikert-Vaikuntanathan IBE [11], respectively. Among them, the first scheme is secure in the standard model, while the other two schemes are secure in the random oracle model. Chow et al. [6] gave three new leakage-resilient IBE schemes from the Boneh-Boyen IBE [2], the Waters IBE [16], and the Lewko-Waters IBE [14], respectively. All of them are secure in the standard model.

Our Contributions. According to [5], IBE schemes from pairings can be classified into three broad families, the full-domain hash family (e.g.

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Boneh-Franklin IBE [3]), the exponent inversion family (e.g. Gentry-IBE [10]), and the commutative blinding family (e.g. Boneh-Boyen IBE [2]). The existing work [1, 6] have shown that IBE schemes from the exponent inversion family and commutative blinding family can be tailored to be leakage-resilient ones. It is natural to ask if we can strengthen the IBE schemes from the full domain hash family to be leakage-resilient.

We give an affirmative answer to the above question by presenting an IBE scheme with the full domain hash structure based on a variant of Boneh-Franklin IBE [7]. Its leakage-resilient chosen plaintext security can be tightly reduced to the DBDH assumption in the relative leakage model and the random oracle model.

2 Preliminaries

Notations. $x \xleftarrow{R} S$ denotes that x is picked uniformly at random from the set S . We write PPT for probabilistic polynomial time. By $\text{negl}(n)$ we denote a negligible function of n . We denote the bit-wise XOR operation by \oplus . We denote by \mathcal{I} the identity space and by \mathcal{SK} the private key space.

2.1 Bilinear Diffie-Hellman Assumption

The decisional BDH (DBDH) assumption [2, 3] is defined via the following game: the challenger runs the bilinear group generator $\text{GroupGen}(1^\kappa)$ to generate $(p, \mathbb{G}, \mathbb{G}_T, e)$, picks four random exponents x, y, z, w from \mathbb{Z}_p , then computes $g^x, g^y, g^z, T_0 = e(g, g)^{xyz}$ and $T_1 = e(g, g)^{xyw}$. We denote by D the tuple $(p, \mathbb{G}, \mathbb{G}_T, e, g, g^x, g^y, g^z)$. The challenger picks a random bit c and gives to the adversary \mathcal{B} the challenge instance (D, T_c) . We say \mathcal{B} succeeds in solving the DBDH problem if it outputs the right guess c' for c at the end of the game, whose advantage is defined as:

$$|\Pr[c = c'] - 1/2| = |\Pr[\mathcal{B}(D, e(g, g)^{xyz}) = 0] - \Pr[\mathcal{B}(D, e(g, g)^{xyw}) = 0]|$$

Definition 2.1 *The (t, ϵ) -DBDH assumption holds if no t -time adversary has at least ϵ in solving the DBDH problem in \mathbb{G} .*

2.2 Randomness Extractors

The following notions and primitives will be used in our construction. We refer the readers to [1, 15] for a complement knowledge.

For a random variable X , we define $\mathbf{H}_\infty(X) = -\log(\max_x \Pr[X = x])$ as its min-entropy. We use the notion of *average min-entropy* [8] which

captures the remaining unpredictability of a random variable X conditioned on another random variable Y , formally defined as

$$\tilde{\mathbf{H}}_{\infty}(X|Y) = -\log(E_{y \leftarrow Y}[\max_x \Pr[X = x|Y = y]])$$

where $E_{y \leftarrow Y}$ denotes the expected value over all values of Y .

The average min-entropy measures exactly the optimal probability of guessing X given knowledge of Y . The following lemma was proved in [9] regarding average min-entropy:

Lemma 1. *For any random variables X, Y, Z , if Y has 2^ℓ possible values, then $\tilde{\mathbf{H}}_{\infty}(X|(Y, Z)) \geq \tilde{\mathbf{H}}_{\infty}(X|Z) - \ell$.*

The statistical distance between two random variables X, Y over a finite domain Ω is defined as

$$\mathbf{SD}(X, Y) = \frac{1}{2} \sum_{\omega \in \Omega} |\Pr[X = \omega] - \Pr[Y = \omega]|$$

Same as [1, 6, 15], a main tool used in our construction is the strong randomness extractor, which is formally defined as follows to the setting of the average min-entropy.

Definition 2.2 *A polynomial-time function $\text{ext} : \mathbb{G} \times \{0, 1\}^\mu \rightarrow \{0, 1\}^m$ is an average case (k, ϵ) -strong extractor if for all pairs of random variables (X, Y) such that $X \in \mathbb{G}$ and $\tilde{\mathbf{H}}_{\infty}(X|Y) \geq k$, we have that*

$$\mathbf{SD}((\text{ext}(X, U_\mu), U_\mu, Y), (U_m, U_\mu, Y)) \leq \epsilon$$

where \mathbb{G} is a non-empty set, and U_μ, U_m are two uniformly distributed random variables over $\{0, 1\}^\mu, \{0, 1\}^m$ respectively.

Dodis et al. [8] proved that any strong extractor is in fact an average-case strong extractor, for a proper setting of the parameters:

Lemma 2. *For any $\delta > 0$, if ext is a worst case $(m - \log(1/\delta), \epsilon)$ -strong extractor, then ext is also an average-case $(m, \epsilon + \delta)$ -strong extractor.*

As a specific example, they proved the following lemma which essentially gives an explicit construction of an average-case strong extractor:

Lemma 3. *Let X, Y be two random variables such that $X \in \mathbb{G}$ and $\tilde{\mathbf{H}}_{\infty}(X|Y) \geq k$. Let $\mathcal{H} = \{H : \mathbb{G} \rightarrow \{0, 1\}^m\}$ be a family of universal hash functions. If $m \leq k - 2\log(1/\epsilon)$ then we have*

$$\mathbf{SD}((H(X), U_s, Y), (U_m, U_s, Y)) \leq \epsilon$$

2.3 Leakage Model for IBE Setting

In this paper we use the relative leakage model suitable for the IBE setting. The leakage-resilient chosen plaintext security is defined by the following **LeakCPA** game, which is refined from the **CpaLeak** game introduced in [6].

Setup. The challenger generates the public parameters mpk and the master secret key msk . It gives mpk to the adversary and keeps msk to itself.

Phase 1. The adversary can make one of the following two types of queries to the challenger:

1. **Leak**(I, h_i) query, where $h_i : \mathcal{SK} \rightarrow \{0, 1\}^{\ell_i}$. The challenger checks if the overall amount leakage will exceed ℓ . If not, it responds with $h_i(sk)$. Otherwise it responds with a reject symbol \perp .
2. **Reveal**(I) query, where I is the identity. The challenger responds with the associated private key sk .

Challenge. The adversary submits two messages M_0, M_1 of equal size and a challenge identity I^* , with the restriction that I^* has not been revealed. The challenger picks a random bit β and encrypts M_β under I^* . It sends the resulting ciphertext C^* to the adversary.

Phase 2. The same as Phase 1 with the restriction that no leakage queries or reveal queries related to I^* are allowed.

Guess. The adversary outputs a bit β' . We say it succeeds if $\beta = \beta'$.

The advantage of an adversary \mathcal{A} on breaking an IBE scheme \mathcal{E} with security parameter κ and leakage bound ℓ is defined as $\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{CPALeak}}(\kappa, \ell) = |\Pr[\beta = \beta'] - \frac{1}{2}|$.

Definition 2.3 *An IBE scheme \mathcal{E} is ℓ -leakage fully secure if for all PPT adversaries \mathcal{A} it holds that $\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{CPALeak}}(\kappa, \ell) \leq \text{negl}(\kappa)$.*

3 Our Scheme

Our scheme consists of the following four algorithms:

Setup. Run $\text{GroupGen}(1^\kappa) \rightarrow (p, \mathbb{G}, \mathbb{G}_T, e)$, pick $x \xleftarrow{R} \mathbb{Z}_p$, $g_2 \xleftarrow{R} \mathbb{G}^*$, and a cryptographic hash function $H : \{0, 1\}^* \rightarrow \mathbb{G}$. Let $g_1 = g^x$, $\ell = \ell(\kappa)$ be an upper bound on the amount of leakage. Then set an average-case $(\log |\mathbb{G}_T| - \ell, \epsilon_{\text{ext}})$ -strong extractor function $\text{ext} : \mathbb{G}_T \times \{0, 1\}^\mu \rightarrow \{0, 1\}^n$. The message space is $\mathcal{M} \in \{0, 1\}^n$, while $mpk = (g, g_1, g_2)$ and $msk = x$.

KeyGen. For a given identity I , pick $t \xleftarrow{R} \mathbb{Z}_p$, compute $u = H(I)$, and then generate the private key for I as $sk = (d_1, d_2) = (t, (ug_2^{-t})^x)$.

Encrypt. To encrypt a message M under identity I , pick an exponent $r \xleftarrow{R} \mathbb{Z}_p$ and a seed $s \xleftarrow{R} \{0, 1\}^\mu$ for the extractor function, generate the ciphertext as $C = (c_1, c_2, c_3, c_4) = (g^r, s, e(g_1, g_2)^r, M \oplus \text{ext}(e(u, g_1)^r, s))$.

Decrypt. To decrypt a ciphertext $C = (c_1, c_2, c_3, c_4)$ encrypted under I using the associated private key $sk = (d_1, d_2)$ to compute $M = c_4 \oplus \text{ext}(e(c_1, d_2)c_3^{d_1}, c_2)$. It is easy to verify that if the private key matches, we get the right decryption.

3.1 Security Analysis

Theorem 3.1 *If the DBDH assumption holds and the extractor's second parameter ϵ_{ext} is negligible in κ , then the proposed scheme is ℓ -leakage secure, where $\ell = \log |\mathbb{G}_T| - k$ and k is the extractor's first parameter.*

To prove the theorem, we organize the proof as a sequence of games, which are defined as follows:

Game_{Real}: The real CPALeak game.

Game_{Final}: The real CPALeak game except in the challenge phase the challenger generates the ciphertext as follows:

$$\begin{aligned} z, w &\xleftarrow{R} \mathbb{Z}_p, \beta \xleftarrow{R} \{0, 1\} & W &= e(u^*, g_1)^z e(g_1, g_2)^{t^*(w-z)} \\ c_1^* &= g^z & c_2^* &\xleftarrow{R} \{0, 1\}^\mu \\ c_3^* &= e(g_1, g_2)^w & c_4^* &= M_\beta \oplus \text{ext}(W, c_2^*) \end{aligned}$$

where t^* is the tag of private key sk^* of the challenge identity I^* , z and w are randomly picked from \mathbb{Z}_p . The challenge ciphertext is $C^* = (c_1^*, c_2^*, c_3^*, c_4^*)$. Note that if $w \neq z$, then C^* is not a valid ciphertext since it is only decrypted correctly when using the private key with tag t^* .

Lemma 3.2 *If there exists a PPT algorithm \mathcal{A} such that $\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}} - \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}} = \epsilon$, then we can build a PPT algorithm \mathcal{B} with advantage ϵ in breaking the DBDH problem.*

Proof. Suppose \mathcal{B} is given a DBDH challenge $(p, \mathbb{G}, \mathbb{G}_T, e, g, g^x, g^y, g^z, T)$. We now describe how it interacts with \mathcal{A} in the following game:

Setup. \mathcal{B} sets $g_1 = g^x$ (implicitly sets $msk = x$), $g_2 = g^y$, picks a suitable extractor function ext , then gives \mathcal{A} the public parameters $mpk = (p, \mathbb{G}, \mathbb{G}_T, e, g, g_1, g_2, \text{ext})$.

Hash queries. For a fresh hash query on I , \mathcal{B} picks $a, t \xleftarrow{R} \mathbb{Z}_p$ and responds with $u = g^a g_2^t$.

KeyGen queries. For an arbitrary identity I , \mathcal{B} computes a private key for it as follows: (1) compute $u = H(I)$; (2) set $d_1 = t$, $d_2 = g_1^a = (ug_2^{-t})^x = (g^a g_2^t g_2^{-t})^x$; (3) return $sk = (d_1, d_2)$.

We note that the keygen queries are always implicitly called by \mathcal{B} when it answers the associated leak queries and reveal queries.

Phase 1. To answer the leak queries and reveal queries issued by \mathcal{A} , \mathcal{B} creates two lists L and K , which are initially empty. L is a list of triples of identities, private keys, and a leakage counter, while K is a list of tuples of identities, private keys.

– **Leak**(I, h_i) query: \mathcal{B} checks if there is a tuple $\langle I, sk \rangle$ in the existing K list. If it is not \mathcal{B} runs $sk \leftarrow \text{KeyGen}(msk, I)$, inserts the tuple (I, sk) to the K list and the triple $\langle I, sk, 0 \rangle$ to the L list. After this step there must exist a triple $\langle I, sk, num \rangle$ in the L list, \mathcal{B} checks if $num + \ell_i \leq \ell$. If this is true, it responds with $h_i(sk)$ and sets $num \leftarrow num + \ell_i$ in $\langle I, sk, num \rangle$. Otherwise \mathcal{B} responds with a reject symbol \perp .

– **Reveal**(I) query: \mathcal{B} checks if there is a tuple $\langle I, sk \rangle$ in the K list. If it is \mathcal{B} responds with sk . If it is not \mathcal{B} runs $sk \leftarrow \text{KeyGen}(msk, I)$, inserts the tuple $\langle I, sk \rangle$ to the K list and the triple $\langle I, sk, 0 \rangle$ to the L list, and responds the leak query with sk .

Notice that \mathcal{B} can calculate a valid private key for any identity. Therefore, \mathcal{B} is able to answer all the leakage queries **Leak**(I, h_i) and reveal queries **Reveal**(I), with the corresponding private key $sk = (d_1, d_2)$.

Challenge. \mathcal{A} submits two messages M_0, M_1 and an identity I^* on which it want to be challenged to \mathcal{B} . \mathcal{B} computes $sk^* = (d_1^*, d_2^*) = (t^*, g_1^{a^*})$, then generates the challenge ciphertext as follows:

$$\begin{aligned} \beta &\xleftarrow{R} \{0, 1\} & c_1^* &= g^z \\ c_2^* &\xleftarrow{R} \{0, 1\}^\mu & c_3^* &= T \\ W &= e(c_1^*, d_2^*)(c_3^*)^{d_1^*} = e(g^z, g_1^{a^*})T^{t^*} & c_4^* &= M_\beta \oplus \text{ext}(W, c_2^*) \end{aligned}$$

Phase 2. The same as Phase 1.

Guess. \mathcal{A} outputs a guess β' . \mathcal{B} returns 0 if $\beta = \beta'$ or 1 if $\beta \neq \beta'$.

We will prove that the advantage of \mathcal{B} in breaking the DBDH problem is ϵ . To see this, notice that if $T = e(g, g)^{xyz}$ the challenge ciphertext is a correct ciphertext according to the original encryption algorithm and thus \mathcal{A} plays the **Game_{Real}**. This is because $W = e(g^z, g_1^{a^*})T^{t^*} = e(g^{a^*}, g_1^z)e(g_2^{t^*}, g_1^z) = e(g^{a^*}g_2^{t^*}, g_1^z) = e(u^*, g_1)^z$ as one can easily verify. Thus the probability that \mathcal{A} succeeds in the game is exactly $\frac{1}{2} + \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}}$. Since \mathcal{B} outputs 0 when \mathcal{A} succeeds we get that

$$\Pr[\mathcal{B}(D, e(g, g)^{xyz}) = 0] = \frac{1}{2} + \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}}$$

On the other hand if $T = e(g, g)^{xyw} = c_3^*$ then \mathcal{A} essentially plays the **Game_{Final}**, because $W = e(g^z, g_1^{a^*})T^{t^*} = e(g^{a^*}, g_1^z)e(g_2^{t^*}, g_1^{(w-z)+z}) = e(u^*, g_1)^ze(g_1, g_2)^{t^*(w-z)}$ as one can easily verify. Therefore we have that

$$\Pr[\mathcal{B}(D, e(g, g)^{xyw}) = 0] = \frac{1}{2} + \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}}$$

Combining the above equations we get that the advantage of \mathcal{B} in DBDH is $|\Pr[\mathcal{B}(D, e(g, g)^{xyz}) = 0] - \Pr[\mathcal{B}(D, e(g, g)^{xyw}) = 0]| = \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}} - \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}} = \epsilon$. Therefore we prove the lemma. \square

Lemma 3.3 *For any PPT adversary \mathcal{A} we have $\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}} \leq 2\epsilon_{\text{ext}}$.*

Proof. In the **Game_{Final}**, it is true that $W = e(u^*, g_1)^ze(g_1, g_2)^{t^*(w-z)}$, where t^* is the tag of the private key for I^* . If we assume that the exact private key with tag t^* is perfect hidden from the adversary, then W distributes uniformly at random in \mathbb{G}_T , and therefore the challenge ciphertext C^* is totally independent of M_β in an PPT adversary \mathcal{A} 's view. This is because $w = z \bmod p$ with negligible probability in κ and t^* is chosen randomly for I^* .

Suppose we denote by R the set of all terms (public parameters, private keys, challenge ciphertext) given to the adversary \mathcal{A} except the leakage, the random seed c_2^* , and the part of the challenge ciphertext c_4^* , then according to the above argument $\tilde{\mathbf{H}}_\infty(C|R) = \log |\mathbb{G}_T|$. But the attacker has access to at most ℓ bits of leakage from the private key, i.e. to a random variable Y with 2^ℓ values, thus by lemma 1 we know that

$$\tilde{\mathbf{H}}_\infty(C|(Y, R)) \geq \tilde{\mathbf{H}}_\infty(C|R) - \ell = \log |\mathbb{G}_T| - \ell$$

According to the definition of $(\log |\mathbb{G}_T| - \ell, \epsilon_{\text{ext}})$ -strong extractor we have that $\mathbf{SD}((\text{ext}(W, S), S, Y, R), (U_m, S, Y, R)) \leq \epsilon_{\text{ext}}$, where S is the random variable for the seed $c_2^* \in \{0, 1\}^\mu$ distributed uniformly at random, Y, R are the values of all the random variables known to the adversary: leakage and the rest, respectively. Thus the statistical distance of $c_4^* = M_\beta \oplus \text{ext}(W, c_2^*)$ from the uniform distribution is at most ϵ_{ext} for each β . The statistical distance between the two possible ciphertexts is at most $2\epsilon_{\text{ext}}$ and no adversary (even an unbounded one) can distinguish them with advantage more than this. \square

Suppose ϵ_{DBDH} is the maximum advantage of all PPT adversaries in the DBDH game. Then according to the above lemma, for any PPT adversary \mathcal{A} we have $\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}} - \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}} \leq \epsilon_{\text{DBDH}}$. Therefore

$$\text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Real}}} \leq \text{Adv}_{\mathcal{A}, \mathcal{E}}^{\text{Game}_{\text{Final}}} + \epsilon_{\text{DBDH}}(\kappa) \leq 2\epsilon_{\text{ext}}(\kappa) + \epsilon_{\text{DBDH}}(\kappa)$$

The proposed scheme is leakage-resilient CPA secure if both $\epsilon_{DBDH}(\kappa)$ and $\epsilon_{\text{ext}}(\kappa)$ are negligible functions of κ . This proves the theorem. \square

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