Secure Length-saving ElGamal Encryption under the Computational Diffie-Hellman Assumption

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Abstract. A design of secure and efficient public key encryption schemes under weaker computational assumptions has been regarded as an important and challenging task. As far as the ElGamal-type encryption is concerned, some variants of the original ElGamal encryption scheme whose security depends on weaker computational assumption have been proposed: Although the security of the original ElGamal encryption is based on the decisional Diffie-Hellman assumption (DDH-A), the security of a recent scheme, such as Pointcheval's ElGamal encryption variant, is based on the weaker assumption, the computational Diffie-Hellman assumption (CDH-A). In this paper, we propose a length-saving ElGamal encryption variant whose security is based on CDH-A and analyze its security in the random oracle model. The proposed scheme is length-efficient which provides a shorter ciphertext than that of Pointcheval's scheme and provably secure against the chosen-ciphertext attack.

1 Introduction

1.1 Encryption Schemes Based on Diffie-Hellman Assumption

Ever since Diffie and Hellman [9] originally proposed the concept of public-key cryptosystem, extensive research has been performed in this field. In particular, the public-key encryption scheme proposed by ElGamal [10] has attracted considerable attention. When ElGamal proposed his public-key encryption scheme, it was widely believed that the security of this scheme is based on the computational assumption called "Diffie-Hellman assumption". Roughly speaking, the Diffie-Hellman assumption says that for a cyclic group G, an adversary who sees g^x and g^y cannot efficiently compute g^{xy}. Often, G is defined as a multiplicative group of a large prime modulo p, *i.e.*, $\mathbb{Z}_p^*$ where g is a generator and $x, y \in \mathbb{Z}_q$. Note here that q is a large prime such that $q|p-1$.

It may be true that the security of ElGamal encryption scheme depends on the Diffie-Hellman assumption since an adversary attacking this scheme cannot decrypt a ciphertext (g^y, mg^{xy}) of a message m without computing g^{xy}. However, indistinguishability [12], which has been accepted as a general security notion of encryption schemes, does not require an attacker to decrypt the whole message. In the notion of indistinguishability, security of encryption scheme implies that an adversary cannot distinguish ciphertexts of two messages chosen by him-or herself. Consequently, it seems that the security of ElGamal encryption should depend on some stronger assumption rather than the Diffie-Hellman assumption. In fact, Tsiounis and Yung [14] showed that the security of ElGamal encryption scheme is not based on the Diffie-Hellman assumption but based on the stronger Decisional Diffie-Hellman assumption (DDH-A). DDH-A says that an adversary who sees two distributions (g^x, g^y, g^{xy}) and (g^x, g^y, R), where R is a randomly chosen-string whose length is the same as g^{xy}, cannot distinguish these two distributions. Hence the Diffie-Hellman assumption is often called the computational Diffie-Hellman assumption (CDH-A) for the purpose of emphasizing an adversary's inability to compute the Diffie-Hellman key, g^{xy}. Throughout this paper, we will use the term CDH-A to refer to the Diffie-Hellman assumption.

1.2 Chosen Ciphertext Security

Ever since Zheng and Seberry [15] initiated a full-scale research on adaptive chosen-ciphertext attacks, the design of public-key encryption schemes has trended toward the prevention of these attacks. In the adaptive chosen-ciphertext attack, an adversary is permitted to access a decryption function as well as an encryption function. The adversary may use this decryption function on ciphertexts chosen after obtaining the challenge ciphertext, with the only restriction that the adversary may not ask for the decryption of the challenge ciphertext itself.

Several security notions on the (adaptive or non-adaptive) chosen-ciphertext attack including non-malleability [8] were formalized and the relationship among them was shown in [3]. Public-key encryption schemes secure against the adaptive chosen-ciphertext attack proposed so far include OAEP [5] (based on the RSA function), the Cramer-Shoup scheme [7] (based on the DDH-A), DHAES [1] (based on the hash Diffie-Hellman assumption (HDH-A)), and the Fujisaki-Okamoto(F-O) scheme [11] (based on the security of any semantically secure public-key encryption schemes). More recently, a general method for converting any partially trapdoor one-way function to the public-key encryption scheme that is secure against the chosen-ciphertext attack was proposed by Pointcheval [13].

The Cramer-Shoup scheme is said to be unique since it does not impose any ideal assumption on the underlying hash function as other schemes do. Although the use of the ideal hash function model, *i.e.*, the random oracle model [4], is still controversial [6], this paradigm often yields much more efficient schemes than those in the standard model [2].

We note here that the underlying computational assumption of Cramer-Shoup scheme is DDH-A, which is much stronger than CDH-A, although the random oracle model is not used in this scheme. The situation remains the same in the ElGamal version of the F-O scheme. However, underlying computational assumption of the ElGamal version of recent Pointcheval's scheme is CDH-A, which is weaker than DDH-A. On the other hand, one deficiency of this scheme is a message expansion. That is, to encrypt a message m, one must compute $(g^{H(m||s)}, rX^{H(m||s)}, G(r) \oplus (m||s))$, where $X(= g^x)$ is a public key, $r \in \mathbb{Z}_p^*$ and

$s \in Z_q$ are appropriate lengths of random strings. Here, both G and H are random oracles. Consequently, the lengths of a ciphertext is 1.5 times longer than that of the original ElGamal version of the F-O scheme.

Based on aforementioned discussions, we propose another ElGamal encryption variant provably secure against chosen-ciphertext attack in the random oracle model. The underlying computational assumption of the proposed scheme is based on CDH-A, but the length of ciphertext is reduced compared with the Pointcheval's scheme.

The organization of this paper is as follows: We briefly review the notions of chosen-ciphertext security for public-key encryption schemes in Section 2. In Section 3, we describe the proposed scheme and analyze its security. In Section 4, comparison of the proposed scheme with other ElGamal variants is provided and concluding remarks will follow in the final section.

2 Notions of Security

Although there are several security notions on the chosen-plaintext attacks and the chosen-ciphertext attacks, we briefly review two notions, the indistinguishability-chosen plaintext attack (IND-CPA) [3, 12] and the plaintext awareness (PA) [3, 5].

Security against the chosen-plaintext attack for public-key encryption schemes is defined by using the following experiment: Let $\mathcal{A}$ be an adversary with two algorithms A_1 and A_2. The "find"-stage algorithm A_1 is run on the public key, pk. At the end of A_1's execution, it outputs a 3-tuple (m_0, m_1, s) where m_0 and m_1 are messages that have the same length and s is a state information. Then one of m_0 and m_1 is selected at random and ciphertext y is determined by encrypting m_b ($b \in_R \{0,1\}$) under pk. The job of the "guess"-stage algorithm A_2 is to determine if y was selected as the encryption of m_0 or m_1, namely to determine the bit b. If the probability that A_2 outputs b is negligible, we say that the public-key encryption scheme is secure in the sense of IND-CPA. Now, we formally define this experiment as follows:

Definition 1 (IND-CPA). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be a public-key encryption scheme, where $\mathcal{K}$, $\mathcal{E}$, and $\mathcal{D}$ denote a key generation algorithm, an encryption algorithm, and a decryption algorithm, respectively. Let $\mathcal{A}(A_1, A_2)$ be an adversary where A_1 denotes a "find"-stage algorithm and A_2 denotes a "guess"-stage algorithm. Also, let (sk, pk) be a secret and public key pair and let s be a state information. If the advantage of $\mathcal{A}$*

$$\begin{aligned} Adv_{\mathcal{A},\Pi}^{\mathrm{IND-CPA}} = 2 \cdot [&(sk, pk) \leftarrow \mathcal{K}; (m_0, m_1, s) \leftarrow A_1(\mathsf{find}, s); b \leftarrow \{0,1\}; \\ &y \leftarrow \mathcal{E}_{pk}(m_b) : A_2(\mathsf{guess}, pk, s, y) = b] - 1 \end{aligned}$$

is negligible, we say that Π is secure in the sense of IND-CPA.

The plaintext awareness (PA), first defined by Bellare and Rogaway [5], formalizes an adversary's inability to create the ciphertext y without "knowing" its corresponding plaintext x.

We note that PA has only been defined in the random oracle model. An adversary $\mathcal{B}$ for PA is given a public key pk and access to the random oracle H. We also provide $\mathcal{B}$ with an oracle for $\mathcal{E}_{pk}^{H}$. The adversary outputs a ciphertext y. To be PA, the adversary $\mathcal{B}$ should necessarily know the decryption m of its output. To formalize this, it is required that there exists an algorithm K (knowledge extractor) that could have output m just by looking at the public key, $\mathcal{B}$'s H-queries and their answers, and the answers to $\mathcal{B}$'s queries to $\mathcal{E}_{pk}^{H}$. The following is a formal definition of PA.

Definition 2 (PA). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be a public-key encryption scheme, let $\mathcal{B}$ be an adversary, let $hH = \{(h_1, H_1), (h_2, H_2), \ldots, (h_{q_H}, H_{q_H})\}$ be a list of all of $\mathcal{B}$'s oracle queries, $h_1, h_2, \ldots, h_{q_H}$, and the corresponding answers $H_1, H_2, \ldots,$ H_{q_H}, and let K be a knowledge extractor. Let $C = \{y_1, y_2, \ldots, y_{q_H}\}$ denote the answers(ciphertexts) as a result of $\mathcal{E}_{pk}^{H}$-queries. For any $k \in \mathsf{N}$ define*

$$\begin{aligned} Succ_{K,\mathcal{B},\Pi}^{\mathrm{PA}} = \Pr[H \leftarrow \mathsf{Hash}; (pk, sk) \leftarrow \mathcal{K}; (hH, C, y) \leftarrow runB^{H, \mathcal{E}_{pk}^{H}(pk)} : \\ K(hH, C, y, pk) = D_{sk}^{H}(y)]. \end{aligned}$$

For $y \notin C$, we say that K is a $\lambda(k)$-extractor if K has running time polynomial in the length of its inputs and for every $\mathcal{B}$, $Succ_{K,\mathcal{B},\Pi}^{PA} \geq \lambda(k)$. We say that Π is secure in the sense of PA if Π is secure in the sense of IND-CPA and there exists a $\lambda(k)$-extractor K where $1 - \lambda(k)$ is negligible.

3 Secure Length-saving ElGamal Encryption Variant

3.1 Description of the Proposed Scheme

Our motivation for constructing the public key encryption scheme whose security relies on CDH-A is to apply random oracle G to Diffie-Hellman key g^{xy}. Since G is assumed to be a random oracle, $G(g^{xy})$ does not reveal any (partial) information about g^{xy}. Hence, to gain any advantage, the adversary must compute g^{xy}. Also, to provide PA, we apply another random oracle H to message m concatenated by some random string s. This motivation leads to the proofs for the theorems provided later in this section. A concrete description of the proposed scheme Π is as follows:

Secure Length-saving ElGamal Encryption Variant $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$

- Key generator $\mathcal{K}$
  $(pk, sk) \leftarrow \mathcal{K}(1^k)$, $pk = (p, q, g, X(= g^x))$ and $sk = (p, q, g, x)$ where $x \in_R \mathrm{Z}_q$, $|p| = k = k_0 + k_1$, and $q | p - 1$, a large prime number.

- Hash Function (two random oracles)
  $H : \{0,1\}^k \rightarrow \mathrm{Z}_q$, and $G : \mathrm{Z}_p^* \rightarrow \{0,1\}^k$

- Encryption $\mathcal{E}$
  $\mathcal{E}_{pk}(m,s) = (\alpha,\beta) = (g^{H(m||s)} \bmod p, G(X^{H(m||s)} \bmod p) \oplus (m||s))$, where message $m \in \{0,1\}^{k_0}$ and $s \leftarrow_R \{0,1\}^{k_1}$

- Decryption $\mathcal{D}$

$$\mathcal{D}_{sk}(\alpha,\beta) = \begin{cases} [\beta \oplus G(\alpha^x \bmod p)]^{k_0} & \text{if } \alpha = g^{H(\beta \oplus G(\alpha^x \bmod p))} \\ \varepsilon(\text{null}) & \text{otherwise} \end{cases}$$

  where $[\beta \oplus G(\alpha^x \bmod p)]^{k_0}$ denotes the first k_0 bit of $[\beta \oplus G(\alpha^x \bmod p)]$.

3.2 Security Analysis

In this section, we show that our ElGamal encryption variant is secure in the sense of IND-CPA under CDH-A and there exists a knowledge extractor K.

Note that the security in the sense of IND-CPA and the existence of a knowledge extractor mean the security in the sense of PA. By the result of [3], this implies security against the adaptive chosen-ciphertext attack (IND-CCA2)

Theorem 1. *If there exists an adversary attacking the encryption scheme $\Pi = (\mathcal{K},\mathcal{E},\mathcal{D})$ in a chosen-plaintext scenario, then we can construct an adversary that breaks CDH-A in the random oracle model with non-negligible probability.*

Proof. Let $\mathcal{A} = (A_1, A_2)$ be an adversary attacking $\Pi = (\mathcal{K},\mathcal{E},\mathcal{D})$ in a chosen-plaintext scenario and ϵ be an advantage of $\mathcal{A}$. Recall that A_1 denotes the "find"-stage algorithm and A_2 denotes the "guess"-stage algorithm. Assume that both G and H are random oracles. Our proving strategy is to use $\mathcal{A}$ to construct an adversary $\mathcal{B}$ that breaks CDH-A. Suppose that $X(=g^x)$ and $Y(=g^y)$ are given to $\mathcal{B}$. $\mathcal{B}$ works as follows:

- First give X, as a public key, to $\mathcal{A}$ and run $\mathcal{A}$. When A_1 makes any oracle query j to G, $\mathcal{B}$ chooses a random string in $\{0,1\}^k$ and answers it as $G(j)$. Similarly, if A_1 makes any oracle query j to H, $\mathcal{B}$ chooses a random string in Z_q and answers it as $H(j)$. A_1 finally outputs two messages m_0 and m_1. $\mathcal{B}$ then selects $b \in \{0,1\}$ at random, takes a random string T in $\{0,1\}^k$ for $G(X^y)$, and outputs $(\alpha,\beta) = (Y, T \oplus (m_b||s))$ as a ciphertext. Then it defines $H(m_b||s)$ as y and $G(X^y)$ as $\beta \oplus (m_b||s)$.
- The ciphertext (α,β) is provided as an input to A_2. Then, A_2 makes oracle queries and $\mathcal{B}$ answers as above.
- When A_2 returns its answer $d \in \{0,1\}$, $\mathcal{B}$ returns a set of all the oracle queries asked to G during the attack.

Now let us define the following two events, $AskG$ and $AskH$.

- $AskG$: The query X^y was made to G.
- $AskH$: The query $m||s$ for some messages m and s chosen at the beginning by $\mathcal{B}$, is made to H.

If $Succ\mathcal{A}$ is an event that A_2 correctly guesses the bit b, *i.e.*, outputs $d = b$, then the advantage of the adversary is defined by $2 \cdot \Pr[Succ\mathcal{A}] - 1$. But, if X^y or $(m_b||s)$ has been already asked to G or H, respectively, the attacker succeeds in guessing the bit b. Hence, $2 \cdot \Pr[Succ\mathcal{A}] - 1 \geq \epsilon$. Since the adversary gains no advantage without $AskG$ or $AskH$, we obtain

$$\Pr[Succ\mathcal{A}] \leq \frac{1}{2} + \frac{\Pr[AskG \vee AskH]}{2}$$

and this leads to $\Pr[AskG \vee AskH] \geq \epsilon$.

Furthermore,

$$\begin{aligned}\Pr[AskG \vee AskH] &= \Pr[AskG] + \Pr[AskH \wedge \neg AskG] \\ &= \Pr[AskG] + \Pr[AskH|\neg AskG]\Pr[\neg AskG] \\ &\leq \Pr[AskG] + \Pr[AskH|\neg AskG]\end{aligned}$$

Yet, the probability that the event $AskH$ takes place is very small provided that $\neg AskG$ is true. More precisely,

$$\Pr[AskH|\neg AskG] \leq \frac{q_H}{2^{k_1}}.$$

Therefore, we have

$$\Pr[AskG] \geq \epsilon - \frac{q_H}{2^{k_1}}.$$

This implies that the probability that X^y lies in the set of all the oracle queries to G is greater than $\epsilon - \frac{q_H}{2^{k_1}}$. Hence if the advantage ϵ of $\mathcal{A}$ is non-negligible, $\mathcal{B}$ breaks CDH-A with non-negligible probability. □

Now we construct a knowledge extractor K. Note that the existence of K implies security in the sense of PA under the assumption that Π is secure in the sense of IND-CPA.

Theorem 2. *Let $\mathcal{B}$ be an adversary for PA. Then there exists a knowledge $\lambda(k)$-extractor K and hence $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ is secure in the sense of PA.*

Proof. Since we have shown that Π is secure in the sense of IND-CPA, we only need to construct a knowledge-extractor K. Assume that $gG = \{(g_1, G_1), (g_2, G_2), \ldots, (g_{q_G}, G_{q_G})\}$, $hH = \{(h_1, H_1), (h_2, H_2), \ldots, (h_{q_H}, H_{q_H})\}$(all the random oracle query-answer pairs of $\mathcal{B}$), $C = \{y_1, y_2, \ldots, y_E\}$(a set of ciphertexts that $\mathcal{B}$ has obtained from the interaction with the random oracles and the encryption oracle), $y = (\alpha, \beta) \notin C$ (a ciphertext produced by $\mathcal{B}$ which is not in C), and the public key X are given to K. The knowledge extractor K works as follows:

- For all gG and hH, K checks that there exists a pair (g_q, h_r) such that $y = (\alpha, \beta) = (g^{H_r}, G_q \oplus h_r)$.

– If there exists one pair, K returns $m = [h_r]^{k_0}$ and s. Otherwise, outputs ε(null).

Next we think of the probability that K outputs the plaintext m correctly, namely $m = \mathcal{D}_{sk}(y)$. Let $Fail$ be an event that $m \neq \mathcal{D}_{sk}(y)$ and let $AskG$ be an event that there exists a pair (g_q, G_q) in the list gG such that $y = (\alpha, \beta) = (g^{H_r}, G_q \oplus h_r)$ for some (h_r, H_r) in the list hH. Similarly, let $AskH$ be an event that there exists a pair (h_r, H_r) in the list hH such that $y = (\alpha, \beta) = (g^{H_r}, G_q \oplus h_r)$ for some (g_q, G_q) in the list gG. Then,

$$\begin{aligned}\Pr[Fail] = &\Pr[Fail|AskG \wedge AskH]\Pr[AskG \wedge AskH] + \\ &\Pr[Fail|\neg AskG \vee \neg AskH]\Pr[\neg AskG \vee \neg AskH] \\ \leq\ & 0 + \Pr[Fail|\neg AskG \vee \neg AskH].\end{aligned}$$

We now determine the upper bound of $\Pr[Fail|\neg AskG \vee \neg AskH]$. For *valid* y, there exist h and g such that $y = (g^{H(h)}, G(g) \oplus h)$. As $y \notin C$, it follows that $h \neq \mathcal{D}(y_i)$ for every $y_i \in C$. However,

$$\begin{aligned}\Pr[valid|\neg AskG \vee \neg AskH] &= \frac{\Pr[valid \wedge (\neg AskG \vee \neg AskH)]}{\Pr[(\neg AskG \vee \neg AskH)]} \\ &\leq \frac{\Pr[valid \wedge \neg AskH]}{\Pr[\neg AskH]} + \frac{\Pr[valid \wedge \neg AskG \wedge \neg AskH]}{\Pr[\neg AskG]} \\ &\leq \Pr[valid|\neg AskH] + \Pr[valid|\neg AskG] \\ &\leq \frac{1}{2^k} + \frac{1}{2^{k_1}}.\end{aligned}$$

On the other hand, if $\neg AskG$ or $\neg AskH$ is true, from the construction of K, it always outputs ε(null), i.e., y is *invalid*. This means that $\Pr[Fail|\neg AskG \vee \neg AskH] = \Pr[valid|\neg AskG \vee \neg AskH] \leq \frac{1}{2^k} + \frac{1}{2^{k_1}}$. Namely, the probability of rejection of valid ciphertext is upper-bounded by $1/2^k + 1/2^{k_1}$. Consequently,

$$\lambda(k) = 1 - \Pr[Fail] \geq 1 - \frac{1}{2^k} - \frac{1}{2^{k_1}}.$$

□

As mentioned before, we get the following corollary from Theorems 1 and 2.

Corollary 1. *The proposed scheme is secure in the sense of IND-CCA2.*

4 Comparison with Other Schemes

We compare the length of ciphertext of the proposed scheme with the original ElGamal encryption scheme and other ElGamal-type encryption schemes such as ElGamal encryption variant of the F-O scheme, and the Pointcheval's ElGamal encryption variant.

For comparison, we briefly describe how four schemes encrypt a message m.

- ElGamal scheme : $(g^y, X^y m)$
- F-O scheme : $(g^{H(m||s)}, X^{H(m||s)} \oplus (m||s))$
- Pointcheval's scheme : $(g^{H(m||s)}, X^{H(m||s)} r, G(r) \oplus (m||s))$
- The proposed scheme : $(g^{H(m||s)}, G(X^{H(m||s)}) \oplus (m||s))$

We summarize the cryptographic characteristics of four schemes in Table 1.

	ElGamal	F-O	Pointcheval	Proposed scheme
Length	$2k$	$2k$	$3k$	$2k$
Number of ROs	None	1	2	2
Assumption	DDH-A	DDH-A	CDH-A	CDH-A
Security	IND-CPA	IND-CCA2	IND-CCA2	IND-CCA2
Comp. for Enc.	2E	2E+H	2E+2H	2E+2H
Comp. for Dec.	E	2E+H	2E+2H	2E+2H

Table 1. Comparison with Other ElGamal Variants, where: $k = |\mathbb{Z}_p^*|$, RO = Random Oracle, E= Exponentiation, H= Random oracle computation, Comp. for Enc.= Computation for Encryption, Comp. for Dec.=Computation for Decryption

As can be seen from the table, the proposed scheme guarantees sound security and length-efficiency. Under the CDH-A, it is secure in the sense of IND-CCA2. We now provide a more detailed explanation on the length of a ciphertext. In the F-O scheme, the length of a ciphertext is $2k$ where $k = |\mathbb{Z}_p^*|$. A ciphertext of the proposed scheme has the same length as those of the original ElGamal scheme and the F-O scheme, when the length of output of G, which is used as the random oracle, is set to k. In the Pointcheval's scheme, the length of ciphertext is extended to $3k$. Compared with the Pointcheval's scheme, the proposed scheme effectively reduces the length of a ciphertext under the same circumstances, *i.e.*, the security of both schemes is based on CDH-A and two random oracles are used. Note that the message to ciphertext ratio of the original ElGamal scheme is the largest since no additional random string follows the message m being encrypted. However, as widely known, the original ElGamal scheme is insecure against chosen-ciphertext attack. The message to ciphertext ratios of other three schemes are the same.

As also can be seen from the table, the computation cost required in the proposed scheme to encrypt and decrypt messages is estimated to be the same as that of the Pointcheval's scheme. Note that we have omitted the computation required to generate public key.

Finally, we mention about implementation of the random oracle G. To implement this function, one can use the heuristic method described in [4] and [5] as follows:

$$G(X^y) = g(\langle 0 \rangle, X^y)||g(\langle 1 \rangle, X^y)||g(\langle 2 \rangle, X^y)|| \ldots,$$

where g is an efficient cryptographic hash function such as SHA-1 or MD5 which outputs 160 bits or 128 bits, respectively, and the notation $\langle i \rangle$ denotes a binary 32-bit word encoding of integer i.

5 Concluding Remarks

In this paper we have proposed another variant of the ElGamal encryption scheme. The security of the proposed scheme depends on CDH-A, which is much weaker than DDH-A. Moreover, the length of a ciphertext is reduced compared with the recent Pointcheval's ElGamal variant, which is based on CDH-A. Also, the proposed scheme provides the same degree of computational efficiency as other proposed schemes.

However, as done in other practical schemes, the random oracle model is employed to provide provable security. A construction of "practical" public-key encryption schemes secure against active adversaries without random oracle other than the one in [7] is an interesting and meaningful future work.

Acknowledgements

The authors would like to thank the anonymous referees for their helpful comments and Prof. Ben Lee at ICU for his proof reading of the final version of this paper.

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