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Proxy Re-encryption Scheme Secured Against Chosen Cipher Text Attack

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Abstract. Recently, proxy re-encryption scheme received much attention. In this paper, we propose a unidirectional proxy re-encryption used to divert ciphertext from one group to another. The scheme is unidirectional and any member can independently decrypt the ciphertexts encrypted to its group. We discuss the security of the proposed scheme and show that our scheme withstands chosen ciphertext attack in standard model.

Keywords. Group-based, Unidirectional, Proxy, Re-encryption, Standard model, V-DDH assumption

1. Introduction

Proxy re-encryption is such a scheme that it allows a proxy to transfer a ciphertext corresponding to Alice's public key into one that can be decrypted by Bob's private key. However, the proxy in this scheme can't obtain any information on the plaintext and the private keys of both users. Manbo and Okamoto firstly introduced the technique for delegating decryption right in [1]. Then, Blaze et al. [3] presented the notion of "atomic proxy cryptography" in 1998.

The proxy re-encryption scheme has been used in some scenarios. For example, Ateniese et al [4] designed an efficient and secure distributed storage system in which the proxy re-encryption scheme is employed. In their system, the Server who storing information is just semi-trusted and no additional means to be used to ensure the security of the system. The Server who acts as a proxy can't get any information about the stored information. There are some other applications, such as secure email forward, and so on [3][6].

In practice, this kind of encryption scheme is divided into two categories by proxy functions, namely bidirectional and unidirectional [2]. In a bidirectional scheme the proxy secret key can be used to divert ciphertext both from Alice to Bob and from Bob to Alice. Obviously, it is very suitable for the scenario where a mutual trust relationship is existent between Alice and Bob. In a unidirectional scheme, the proxy secret key is only allowed to divert ciphertext either from Alice to Bob or from Bob to Alice.

Group communication is a useful primitive for sharing message in a specifically group and has been widely used in unbalanced networks, for example, clusters of mobile devices [15]. Ma et al. [5] designed an efficient encryption scheme to ensure the privacy of the messages shared in the group. In the scheme, anyone can encrypt a message and distribute it to a designated group and any member in the designated group can decrypt the ciphertext. In group communication scenarios, the proxy re-encryption scheme can be employed to solve some problems between two different groups. For example, due to the change of duty, some work managed by group A has been assigned to group B such that some encrypted documents sent to group A should be decrypted by group B. In such scenario, proxy re-encryption technique can be used to realize this transformation.

Motivated by above mentioned, we present a group-based proxy re-encryption scheme in this paper. It is a unidirectional scheme, i.e. the proxy using one secret key can divert ciphertext either from group A to group B or from group B to group A.

The rest of paper consists of following sections. In section 2, we introduce some related works. In section 3, we give the security model and complexity assumptions. The proposed group-based proxy re-encryption scheme is presented in section 4. In section 5, we discuss the security of the proposed scheme in standard model. Finally, we draw the conclusions in section 6.

2. Related works

The notion of "atomic proxy cryptography" was presented by Blaze et al. [3] in 1998. It provides securer and more efficient way than usual to deal with the scenario in which a proxy decrypts a ciphertext using Alice's private key and then encrypts the result using Bob's public key.

In 2003, Ivan and Dodis [2] designed proxy encryption for Elgamal, RSA, and an IBE scheme using secret sharing technique. In their Elgamal based scheme, PKG generates encrypt key EK and decrypt key DK for each user, and then DK is divided into two parts x_1 and x_2, which satisfy DK= $x_1 + x_2$. Moreover, they designed unidirectional and bidirectional proxy encryption scheme.

Following the work of Ivan and Dodis, Ateniese et al. [4] presented an improved proxy re-encryption scheme, and employed it in distributed storage system. In their re-encryption scheme, the proxy only preserves a discrete value to prevent the collude attack.

Recently, Canetti and Hohenberger [6] proposed a proxy re-encryption scheme secure against chosen ciphertext attack. They discuss its security in standard model. There are some other re-encryption schemes, such as Jakobsson's quorum controlled asymmetric proxy re-encryption [7], and the identity-based scheme presented by Green and Ateniese [8]. There are some investigations on proxy signature schemes [9][10].

Many papers in the literature—the first one of which being [38]—consider applications where data encrypted under a public key should eventually be encrypted under a different key . In proxy encryption schemes [24], [33], a receiver Alice allows a delegatee Bob to decrypt ciphertexts intended for her with the help of a proxy by providing them with shares of her private key. This requires delegatees to store an additional secret for each new delegation. Dodis and Ivan [24] present efficient proxy encryption schemes based on RSA, the Decision Diffie–Hellman problem as well as in an identity-based setting [15], [42] under bilinear-map-related assumptions. Proxy re-encryption schemes are a special kind of proxy cryptosystems where delegatees only need to store their own decryption key. They find applications in secure e-mail forwarding, digital rights management (DRM) or distributed storage systems (e.g., [4] and [5]). The signature analogue, also suggested by Blaze *et al.* [11] in 1998, of PRE systems was formalized by Ateniese and Hohenberger [6] in 2005. The two techniques were notably combined [44] to design interoperable DRM systems where digital content can be translated between devices from different DRM domains. From a theoretical point of view, the first positive obfuscation result for a complex cryptographic functionality was recently presented by Hohenberger, Rothblum, shelat and Vaikuntanathan [32]: they proved the existence of an efficient program obfuscator for a family of circuits implementing re-encryption. In [29], Green and Ateniese studied the problem of identity- based PRE and proposed a unidirectional scheme that can be made chosen-ciphertext secure. Their security results are presented only in the random oracle model. Also, the recipient of a re-encrypted ciphertext needs to know who the original receiver was in order to decrypt a re-encryption. In the standard model, Chu and Tzeng [23] described another identity-based PRE scheme that extends to provide chosen-ciphertext security. Their scheme is both multihop and unidirectional but fails to provide collusion-resistance (also called *master secret security* in [4] and [5]) as the delegator's private key is trivially exposed when a dishonest delegatee and a proxy pool their information.

3. Background

3.1 Bilinear map

Let G_1 be a cyclic multiplicative group generated by g, whose order is a prime q and G_2 be a cyclic multiplicative group of the same order q. Assume that the discrete logarithm in both G_1 and G_2 is intractable. A bilinear pairing is a map $e: G_1 \times G_1 \to G_2$ and satisfies the following properties:

1. *Bilinear:* $e(g^a, p^b) = e(g, p)^{ab}$. For all g, $p \in G_1$ and $a, b \in \mathbf{Z}_q$, the equation holds.
2. *Non-degenerate:* There exists $p \in G_1$, if $e(g, p) = 1$, then $g = O$.
3. *Computable:* For g, $p \in G_1$, there is an efficient algorithm to compute $e(g, p)$.
4. *commutativity:* $e(g^a, p^b) = e(g^b, p^a)$. For all g, $p \in G_1$ and $a, b \in \mathbf{Z}_q$, the equation holds.

Typically, the map e will be derived from either the Weil or Tate pairing on an elliptic curve over a finite field. Pairings and other parameters should be selected in proactive for efficiency and security [11].

3.2 Complexity assumptions

— ***Computational Diffie-Hellman Assumption***

Given g^a and g^b for some $a, b \in \mathbf{Z}_q^*$, compute $g^{ab} \in G_1$. A (τ, ε)-CDH attacker in G_1 is a probabilistic machine Ω running in time τ such that

$$Succ_{G_1}^{cdh}(\Omega) = \Pr[\Omega(g, g^a, g^b) = g^{ab}] \geq \varepsilon$$

where the probability is taken over the random values a and b. The CDH problem is (τ, ε)-intractable if there is no (τ, ε)-attacker in G_1. The CDH assumption states that it is the case for all polynomial τ and any non-negligible ε.

— ***Decisional Bilinear Diffie-Hellman Assumption [12]***

We say that an algorithm π that outputs $b \in \{0,1\}$ has advantage ε in solving the **Decisional Bilinear Diffie-Hellman** (**DBDH**) problem in G_1 if

$$|\Pr[\pi(g, g^a, g^b, g^c, e(g,g)^{abc}) = 0] - \Pr[\pi(g, g^a, g^b, g^c, T) = 0]| \geq \varepsilon$$

where the probability is over the random bit of π, the random choice of $a, b, c \in \mathbf{Z}_q^*$, and the random choice of $T \in G_2$. The **DBDH** problem is intractable if there is no attacker in G_1 can solve the **DBDH** with non-negligible ε.

— ***V-Decisional Diffie-Hellman Assumption***

An algorithm π that outputs $b \in \{0,1\}$ has advantage ε in solving the **V-Decisional Diffie-Hellman** (**V-DDH**) problem in G_1 if

$$|\Pr[\pi(g, g^a, g^{ab}, g^{ac}, g^{bc}) = 0] -$$

$$\Pr[\pi(g, g^a, g^{ab}, g^{ac}, T) = 0] \geq \varepsilon$$

where the probability is over the random bit of π, the random choice of $a, b, c \in \mathbf{Z}_q^*$, and the random choice of $T \in G_1$. The **V-DDH** problem is intractable if there is no attacker in G_1 can solve the **V-DDH** with non-negligible ε.

3.3 Security notions

The proposed re-encryption scheme consists of five algorithms, namely **KeyGen**, **ReKeyGen**, **Enc**, **ReEnc** and **Dec**.

— **KeyGen** (1^λ). On input the security parameter, outputs the public key PK of each group and the corresponding private key d_i for each member.

— **ReKeyGen** (sk_1, sk_2). On input two private key sk_1 and sk_2, outputs a unidirectional re-encryption key $rk_{1\to 2}$.

— **Enc** (PK, m). On input message $m \in \{0,1\}^*$ and a public key PK, outputs a ciphertext C.

— **ReEnc** $(rk_{1\to 2}, C_1)$. On input ciphertext C_1 and the re-encryption key $rk_{1\to 2}$, outputs a ciphertext C_2 or an error symbol $\perp$.

— **Dec** (sk, C). On input ciphertext C and a private key sk, outputs the corresponding message m.

The indistinguishable chosen ciphertext attack (IND-CCA) [13] presented by Goldwasser and Micali has been widely used to analyze the security of an encryption scheme. In this model, several queries are available to the attacker to model his capability. Subsequently, Rackhoff and Simon [14] enhanced it and proposed adaptively chosen ciphertext attack (IND-CCA2). Since this notion is stronger, it is becoming a prevalent model in analyzing encryption scheme. Green and Ateniese [8] enhanced the model and used it to discuss the security of proxy re-encryption scheme, then followed by Canetti and Hohenberger [6].

In this part, we define adaptively chosen ciphertext security of the group-based proxy re-encryption scheme. Compared to the model mentioned in [6], we don't consider the case of group A or B's corruption due to the properties of our key generation. Security is defined using the following game between an *Attacker* and *Challenger*.

1. **Setup.** The *Challenger* initializes the system and gives the *Attacker* the resulting system parameters and the public key PK. It keeps private key to itself.
2. **Query phase 1.**
   - **Decrypt queries.** The *Attacker* issues a query (c_{i1}, c_{i2}, c_{i3}). The *Challenger* outputs **Decrypt** (c_{i1}, c_{i2}, c_{i3}), otherwise outputs error symbol $\perp$.
   - **Re-encrypt queries**. The *Attacker* issues a query (c_{i1}, c_{i2}, c_{i3}) encrypted using the public key of group A. The *Challenger* outputs **Re-encrypt** $(rk_{A\to B}, c_{i1}, c_{i2}, c_{i3})$. Obviously, the output is a ciphertext encrypted using the public key of group B.

   The *Attacker* is allowed to perform the **Query phase 1** several times.
3. **Challenge.** Once the *Attacker* decides that **Query phase 1** is over, the *Attacker* outputs two equal length messages $\{M_0, M_1\}$ to the *Challenger*. Upon receiving the messages, the *Challenger* chooses a random bit $e \in \{0,1\}$, invokes **Encrypt** (PK_A, M_e) and outputs (c_1^*, c_2^*, c_3^*) as the answer.
4. **Query phase 2.** The *Attacker* continues to adaptively issue **Decrypt** queries and **Re-encrypt** queries. The *Challenger* responds as in the phase 1. These queries may be asked adaptively as in **Query phase 1**, but the query on (c_1^*, c_2^*, c_3^*) is not permitted.
5. **Guess.** Finally, the *Attacker* outputs a guess $e' \in \{0,1\}$ for e and wins the game if $e' = e$.

The encryption scheme is secure against chosen ciphertext attack, if the *Attacker* has a negligible advantage $\varepsilon = \left|\Pr(e = e') - \frac{1}{2}\right|$ to win the game.

4. The proposed unidirectional proxy re-encryption scheme

We assume that there exist two groups in our scheme, namely A and B. The function of the Proxy is to transform ciphertext corresponding to the public key of group A into ciphertext for the public key of group B without revealing any information about the secret decryption keys or the clear text, and vice versa. It means that our proxy re-encryption is a bidirectional scheme. The proposed scheme consists of following steps.

4.1 Initialize

Let G_1 be a cyclic multiplicative group generated by g, whose order is a prime q and G_2 be a cyclic multiplicative group of the same order q. A bilinear pairing is a map: $e: G_1 \times G_1 \to G_2$ that can be efficiently computed.

PKG chooses $a, b \in \mathbf{Z}_q^*$ and $h \in G_1$ uniformly at random, and then computes $g_1 = g^a$ and $g_2 = g^b$. The master private keys are a and b, and the master public keys are g_1, g_2 and h.

4.2 Key Generation

PKG chooses $k \in \mathbf{Z}_q^*$ uniformly at random as the tag of the group A. Using $PK_{A1} = g_1^k$, $PK_{A2} = g_2^k$ as group A's public keys. The private keys of the member $p_i \in A$ can be generated as follows:

1. PKG chooses $r_i \in \mathbf{Z}_q^*$ uniformly at random.

2. compute and output $d_{i1} = h^{r_i} \cdot g^{k \cdot r_i}$, $d_{i2} = h^{(r_i - k^{-1})b^{-1}} \cdot g^{a \cdot k \cdot r_i \cdot b^{-1}}$, and $d_{i3} = g \cdot h^{r_i}$.

The member p_i's private key is $d_i = \{d_{i1}, d_{i2}, d_{i3}\}$. PKG chooses $l \in Z_q^*$ uniformly at random as the tag of the group B and publishes $PK_{B1} = g_1^l$, $PK_{B2} = g_2^l$ as group B's public keys. The private keys of the member $p_i \in B$ can be similarly generated as above.

4.3 Encrypt

In order to encrypt a message $\mathrm{M} \in \{0,1\}^{\lambda}$ for the group A, the sender first chooses $s \in \mathbf{Z}_q^*$ uniformly at random, and computes the ciphertext

$$c_1 = e(g_1, PK_{A1})^s \cdot \mathrm{M} \qquad c_2 = (h \cdot PK_{A1})^s \qquad c_3 = (PK_{A2})^s.$$

The ciphertext for message M is $c = (c_1, c_2, c_3)$. The sender sends the ciphertext to all the members in the group A by broadcast over Internet.

4.4 Re-encrypt

In order to transform the ciphertext to group B, PKG generates a Re-encrypt keys

$$Key^1_{A\to B} = g^{\left(\frac{k-l}{k}\right)ab^{-1}} \qquad Key^2_{A\to B} = ab^{-1} \qquad Key^3_{A\to B} = \frac{l}{k}$$

and sends it to $\Pr oxy$. Then using the Re-encrypt key, the proxy can perform

$$\begin{aligned}\tilde{c}_1 &= c_1 \cdot e(c_3, Key^1_{A\to B}) \\ &= e(g_1, g^k)^s \cdot \mathrm{M} \cdot e(g_2^{ks}, g^{\left(\frac{k-l}{k}\right)ab^{-1}}) \\ &= e(g_1, g^{ks}) \cdot \mathrm{M} \cdot e(g,g)^{(k-l)as} \\ &= e(g_1, g^{ls}) \cdot \mathrm{M} = e(g,g)^{asl} \cdot \mathrm{M}\end{aligned}$$

$$\tilde{c}_3 = (c_3)^{Key^3_{A\to B}} = (c_3)^{l \cdot k^{-1}} = g_2^{k \cdot s \cdot l \cdot k^{-1}} = (g_2^l)^s$$

$$\tilde{c}_2 = \frac{c_2 \cdot c_3^{(Key^2_{A\to B}) \cdot (Key^3_{A\to B})}}{c_3^{Key^2_{A\to B}}} \quad \frac{c_2 \cdot c_3^{a \cdot b^{-1} \cdot l \cdot k^{-1}}}{c_3^{a \cdot b^{-1}}} = h^s \cdot g_1^{l \cdot s} = (h \cdot g_1^l)^s.$$

The Re-encrypted ciphertext is $(\tilde{c}_1, \tilde{c}_2, \tilde{c}_3)$.

4.5 Decrypt

After receiving the re-encrypted message $c = (\tilde{c}_1, \tilde{c}_2, \tilde{c}_3)$, the member $p_i \in B$ can decrypt the ciphertext as follows:

1. compute $T = e(\tilde{c}_2, d_{i3}) e(\tilde{c}_3, d_{i2}) / e(\tilde{c}_2, d_{i1})$.
2. compute $M = \tilde{c}_1 / T$.

Any member $p_i \in B$ can compute T correctly, since

$$\begin{aligned}T &= \frac{e(\tilde{c}_2, d_{i3}) e(\tilde{c}_3, d_{i2})}{e(\tilde{c}_2, d_{i1})} \\ &= \frac{e(h^s g^{als}, g \cdot h^{r_i}) e(g_2^{ls}, h^{(r_i - l^{-1})b^{-1}} g^{alr_i b^{-1}})}{e(h^s g^{als}, h^{r_i} g^{lr_i})} \\ &= \frac{e(h^s, g) e(h^s, h^{r_i}) e(g^{als}, g) e(g^{als}, h^{r_i})}{e(h^s, h^{r_i}) e(h^s, g^{lr_i})} \\ &\cdots \frac{e(g_2^{ls}, h^{(r_i - l^{-1})b^{-1}}) e(g_2^{ls}, g^{alr_i b^{-1}})}{e(g^{als}, h^{r_i}) e(g^{als}, g^{lr_i})} \\ &= e(g^{als}, g) = e(g,g)^{als}\end{aligned}$$

So the member p_i can get the plaintext

$$M = \tilde{c}_1 / T$$

To the user in group A, he can get the plaintext M from (c_1, c_2, c_3) similarly to the user in group B.

5. Security

In this section, we will discuss the security of the proposed proxy re-encryption scheme in standard model. The measure used to prove our scheme comes from the paper [6].

Lemma. *Suppose the* ***CDH*** *assumption holds. Then given* $g^a, g^{ab}, g^{ac} \in \mathrm{G}_1$, *computing* g^{bc} *is intractable.*

Proof. Assume that given $g^a, g^{ab}, g^{ac} \in \mathrm{G}_1$, the attack Alice has ability to compute another g^{bc}. Then we can design an algorithm to solve CDH problem. In other words, given $g^m, g^n \in \mathrm{G}_1$, the challenger Bob can compute $g^{m \cdot n}$ by running Alice as a subroutine.

To the given $g^m, g^n \in \mathrm{G}_1$, Bob chooses a random number $t \in \mathbf{Z}_q^*$, computes g^{mt} and g^{nt}, and then sends g^t, g^{mt} and g^{nt} to Alice. With the assumption, Alice can output $g^{m \cdot n}$, then Bob can solve CDH problem.

□

Theorem. *Suppose that the* ***V-DDH*** *is intractable. Then our proxy re-encryption scheme is secure against adaptively chosen ciphertext attack.*

Proof. Assume that if the attacker Alice has ability to break the proposed encryption scheme via chosen ciphertext attack with non-negligible probability ε, then we can prove that there exists challenger Bob that can solve **V-DDH** problems with the same probability. In other words, given $g^{a^*}, g^{a^* s^*}, g^{a^* k^*} \in \mathrm{G}_1$ and $T \in \mathrm{G}_1$, Bob can decide if T is equal to $g^{s^* k^*}$ with non-negligible probability by running Alice as a subroutine. The challenger Bob interacts with Alice by simulating **Decrypt**, **Re-encrypt** oracles.

Bob initializes the system, chooses random numbers $w, v \in \mathbf{Z}_q^*$. Let

$$g_1 = g^{a^*} \qquad g_2 = g^{a^* \cdot w} \qquad PK_{A1} = g^{a^* k^*}$$

$$PK_{A2} = g^{a^* k^* v} \qquad h = g^{a^* \cdot k^* \cdot w}.$$

Then Bob chooses a random number $\alpha \in \mathbf{Z}_q^*$ and publishes $PK_{B1} = g^{a^* \cdot k^* \cdot \alpha}$ and $PK_{B2} = g^{a^* \cdot k^* \cdot v \cdot \alpha}$.

Query phase 1.

- **Decrypt queries**. To every new query (c_1, c_2, c_3), Bob computes and outputs $M = c_1 / e(g_1, c_3^{1/w})$ as the answer.
- **Re-encrypt queries**. To every new query (c_1, c_2, c_3), Bob computes

$$\begin{aligned}\tilde{c}_1 &= e(g_1, P_{A1})^s \cdot \mathrm{M} \cdot e(c_3^{1/w}, g^{a^* \alpha - a^*}) \\ &= e(g^{a^*}, g^{a^* k^*})^s \cdot \mathrm{M} \cdot e(g^{a^* k^* s}, g^{a^* \alpha - a^*}) \\ &= e(g,g)^{a^* a^* k^* s + a^* a^* k^* s \alpha - a^* a^* k^* s} \cdot \mathrm{M}\end{aligned}$$

$$= e(g,g)^{a^*a^*k^*s\alpha} \cdot \mathrm{M} = e(g_1, P_{B1})^s \cdot \mathrm{M}$$

$$\tilde{c}_3 = (c_3)^\alpha$$

$$\tilde{c}_2 = c_2 \cdot (c_3)^{-v^{-1}} \cdot (c_3)^{v^{-1}\cdot\alpha}$$

And then, Bob outputs $(\tilde{c}_1, \tilde{c}_2, \tilde{c}_3)$ as the answer.

Since $w, \alpha \in \mathbf{Z}_q^*$ are two random number, Alice can't distinguish the simulated answers from the actual results. Thereby, we say above simulation is perfect. Alice is allowed to perform **Decrypt** and **Re-encrypt** queries several times.

Challenge phase. When Alice decides Query phase 1 is over, she chooses two equal length messages $\mathrm{M}_1, \mathrm{M}_0$, and sends them to Bob. Bob chooses a random bit $e \in \{0,1\}$, computes and outputs

$$c_1^* = e(g_1, T) \cdot \mathrm{M}_e = e(g^{a^*}, g^{a^* \cdot k^*})^{s^*/a^*} \cdot \mathrm{M}_e$$

$$c_2^* = (T)^{(w+1)} = (g^{k^*s^*})^{(w+1)} = (g^{a^* \cdot k^* \cdot w} \cdot g^{a^* \cdot k^*})^{s^*/a^*}$$

$$c_3^* = (T)^w = (g^{k^*s^*})^w = (g^{a^*k^*w})^{s^*/a^*}$$

as the answer. The **Challenge phase** can be performed only once.

Query phase 2. Alice continues to adaptively issue **Decrypt** and **Re-encrypt** queries. Bob responds as in the phase 1. However, the query on (c_1^*, c_2^*, c_3^*) is not permitted.

Guess. Finally, Alice outputs a guess $e' \in \{0,1\}$ for e. If $e' = e$, then Bob decides $T = g^{s^*k^*}$, otherwise Bob decides $T \neq g^{s^*k^*}$.

Obviously, above simulation is perfect. We say that Alice can break the proxy re-encryption scheme with non-negligible probability ε. It means that Alice can output correct e' with probability ε. Then Bob can solve the **V-DDH** with same probability ε by running Alice as a subroutine.

□

6. Conclusions

Recently, most researchers focused their attention on how to convert ciphertext for one user into ciphertext for another without revealing underlying plaintext. According to the proxy function, we can divide these schemes into two categories: bidirectional and unidirectional. In this paper, we extend this notion and present bidirectional proxy re-encryption scheme used for group communications. In our scheme, the proxy diverts the ciphertext for group A into ciphertext for group B, and vice versa. To the member in group A/B, he can independently decrypt the ciphertext for the group.

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