Cryptanalysis of A Multi-use CCA-secure Proxy Re-encryption Scheme

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Abstract

Proxy re-encryption (PRE) can be classified as single-hop PRE and multi-use PRE according to the times which the ciphertext is transformed. Finding a unidirectional, multi-use, and chosen ciphertext attack (CCA) secure PRE is presented as an open problem by Canetti et al. Wang claimed to resolve this problem by proposing the first multi-use CCA-secure unidirectional PRE scheme. But Zhang et al. have shown their proposal is not CCA-secure by giving concrete attacks. In this paper, we propose an improvement for Wang-Multi-Use-PRE to resist Zhang's attack. But we also found that different with single-hop PRE, multi-use PRE without randomize encrypt key in its re-encryption algorithm could be vulnerable to attack. According to this principle we find a new type attack to multi-use CCA-secure PRE named proxy bypass attack. Then we give concrete attacks on Wang-Multi-Use-PRE scheme. This attack is also effective for other multi-use scheme.

Keywords: *Proxy re-encryption, multi-use, chosen ciphertext security*

1. Introduction

In Eurocrypt 98, Blaze, Bleumer and Strauss [3] proposed a concept called proxy re-encryption (PRE). A semi-trusted proxy can transform a ciphertext encrypted for Alice into a ciphertext for Bob, while proxy does not get any useful information about plaintext or key. Ateniese, *et al.*, [2] proposed the first unidirectional proxy re-encryption scheme and propose a series of properties of PRE schemes. In ACNS2007, Green [7] introduced an Identity-Based Proxy Re-Encryption (IB-PRE) scheme and defined the multi-use property. In ACM CCS 2007, Canetti and Hohenberger [4] brought out an open problem, that is how to construct a multi-use CCA-secure unidirectional PRE scheme.

Recently, Wang, *et al.*, [12, 13] claimed to answer this problem by proposing the first multi-use CCA-secure unidirectional PRE scheme. But in INCoS 2012, Zhang, *et al.*, [18-20] have shown their proposal is not CCA-secure in the corresponding security models. In this article, we argue that Zhang's attack is easy to fix. But there exists another attack to Wang-Multi-Use-PRE in regard to its multi-use property. This attack is also universally effective for other multi-use scheme.

Proxy re-encryption has been coming up for eight years now [3]. In 2006 year Ateniese et al. [2] proposed the first unidirectional proxy re-encryption scheme, but it is only CPA-secure.

Since then a number of PRE schemes with different properties have been proposed in the literature (*e.g.*, [1, 2, 4, 6, 8, 9, 14–17]).

In ACNS2007, Green [7] introduced an Identity-Based Proxy Re-Encryption (IB- PRE) scheme and defined the multi-use property. A multi-use scheme permits the proxy (or proxies) to perform multiple re-encryptions on a single ciphertext, *e.g.*, re-encrypts from A to B, then re-encrypts the result from B to C, etc. They brought out a notion of “encryption level”, as an implicit property of a ciphertext. After that, there have been some papers [5, 10, 12, 13,21] proposed multi-use PRE schemes.

In this article, we propose an improvement for Wang-Multi- Use-PRE to resist Zhang’s attack. And then we introduce an attack named proxy bypass attack. The attack is against the PRE schemes that are extended from single- hop to multi-use and without randomize encrypt key in their re-encrypt algorithms. It’s effective to Wang-Multi-Use-PRE and also effective for some multi-use schemes such as case scheme [5, 13].

The rest of this paper is organized as follows. We review the framework of Multi-Use-PRE and Wang-Multi-Use-PRE scheme in Section 2. In Section 3, we describe Zhang’s attack and propose an improvement for Wang-PRE scheme to resist Zhang’s attack. And in Section 4, we propose a new general attack named proxy bypass attack, then give a concrete attack on Wang-multi-use PRE scheme and discuss the flaw exist in other schemes. Finally we conclude this paper in Section 5.

2. Framework of Multi-Use-PRE Scheme

In this section, we review the definition and security notions for Multi-Use-PRE as formalized by Zhang [18].

2.1. Multi-Use-PRE Scheme Definition

A multi-use unidirectional proxy re-encryption scheme is a tuple of algorithms (Key- Gen, ReKeyGen, Encrypt, ReEncrypt, Decrypt):

- $\text{KeyGen}(1^k) \rightarrow (pk, sk)$: Taking as input a security parameter k , this algorithm returns a public key pk and a secret key sk .
- $\text{ReKeyGen}(sk_i, pk_j) \rightarrow rk_{i \rightarrow j}$: Given user i ’s secret key sk_i and user j ’s public key pk_j , this algorithm outputs a re-encryption key $rk_{i \rightarrow j}$.
- $\text{Encrypt}(pk, m) \rightarrow C_{pk}^{(1)}$: Given a public key pk and a message $m \in \{0, 1\}^n$, this algorithm outputs a first-level ciphertext $C_{pk}^{(1)}$.
- $\text{ReEncrypt}(rk_{i \rightarrow j}, C_{pk_i}^{(l)}) \rightarrow C_{pk_j}^{(l+1)}$ ($l \geq 1$): Given a re-encryption key $rk_{i \rightarrow j}$, a l -level ciphertext $C_{pk_i}^{(l)}$ under pk_i , outputs a $(l + 1)$ -level ciphertext $C_{pk_j}^{(l+1)}$ under pk_j or $\perp$.
- $\text{Decrypt}(sk_i, C_{pk_i}) \rightarrow m$: Given a l -level ciphertext C_{pk_i} under pk_i , outputs a message m or $\perp$.

2.2. CCA-security of Multi-Use-PRE Scheme

Before defining the CCA-security of Multi-Use-PRE Scheme, we introduce a notion challenge derivative which is defined by [11]. The definition of challenge derivative is as follows:

1. (pk^*, C^*) is a challenge derivative of itself.
2. If $(pk_i, C_{pk_i}^{(l)})$ is a challenge derivative, $\mathcal{A}$ has issued the query $\mathcal{O}_{\text{RE-Enc}}(pk_i, pk_j, C_{pk_i}^{(l)})$ to receive a new ciphertext $C_{pk_j}^{(l+1)}$, then $(pk_j, C_{pk_j}^{(l+1)})$ is a challenge derivative.

3. If $(pk_i, C_{pki}^{(l)})$ is a challenge derivative, $\mathcal{A}$ has issued the query $\mathcal{O}_{RE-EXT}(pk_i, pk_j)$ to obtain a re-encryption key $rk_{i \rightarrow j}$, and a $(l+1)$ -level ciphertext $C_{pkj}^{(l+1)} = \text{ReEncrypt}(rk_{i \rightarrow j}, C_{pki}^{(l)})$, then $(pk_j, C_{pkj}^{(l+1)})$ is a challenge derivative.

Now, we review the CCA-secure definition of multi-use unidirectional PRE scheme. Notice that the definition is in the static corruption model, where the adversary should decide the corrupted users before the game starts.

A multi-use unidirectional PRE scheme is CCA-secure if the advantage of any PPT adversary $\mathcal{A}$ in the following game played between a challenger $\mathcal{C}$ and $\mathcal{A}$ is negligible in the security parameter k .

- Setup Phase: The challenger takes a security parameter k and generate the public parameters $params$.
- Phase 1: $\mathcal{A}$ issues queries $q_1, \dots, q_m$ adaptively, where q_i is one of the following oracles queries:
 - $\mathcal{O}_{KeyGen}(i)$: $\mathcal{C}$ runs algorithm $\text{KeyGen}(1^k)$ to generate a key pair (pk_i, sk_i) , outputs pk_i .
 - $\mathcal{O}_{EXT}(pk_i)$: $\mathcal{C}$ outputs user i 's private key sk_i corresponding to public key pk_i .
 - $\mathcal{O}_{RE-EXT}(pk_i, pk_j)$: $\mathcal{C}$ runs algorithm $\text{ReKeyGen}(sk_i, pk_j) \rightarrow rk_{i \rightarrow j}$ to generate a re-encryption key $rk_{i \rightarrow j}$, where sk_i is the secret key corresponding to pk_i .
 - $\mathcal{O}_{RE-Enc}(pk_i, pk_j, C_{pki}^{(l)})$: $\mathcal{C}$ returns $C_{pkj}^{(l+1)} = \text{ReEncrypt}(rk_{i \rightarrow j}, C_{pki}^{(l)})$.
 - $\mathcal{O}_{DEC}(pk_i, C_{pki}^{(l)})$: $\mathcal{C}$ returns $\text{Decrypt}(sk_i, C_{pki}^{(l)})$, where sk_i is the secret key corresponding to pk_i .
- Challenge: Once $\mathcal{A}$ decides that Phase 1 is over, it outputs two equal-length plaintexts $m_0, m_1 \in \mathcal{M}$ and a public key pk^* corresponding to an uncorrupted private key, on which it wishes to be challenged. Moreover, $\mathcal{A}$ is restricted to the choice of pk^* that trivial decryption is not possible using keys extracted in Phase 1, e.g., by using re-encryption keys to transform C_{pk^*} into C_{pki} for which $\mathcal{A}$ holds a decryption key. The challenger picks a random bit $b \in \{0, 1\}$ and computes the challenge ciphertext $C^* = \text{Encrypt}(m_b, params, pk^*)$. It sends C^* as the challenge to $\mathcal{A}$.
- Phase2: $\mathcal{A}$ issues queries $q_{m+1}, \dots, q_n$ adaptively, where q_i is one of the following oracles queries:
 - $\mathcal{O}_{EXT}(pk_i)$: $\mathcal{C}$ responds as in Phase1 except a challenge derivative $(pk_i, C_{pki}^{(l)})$ exists.
 - $\mathcal{O}_{RE-EXT}(pk_i, pk_j)$: $\mathcal{C}$ responds as in Phase1 except a challenge derivative $(pk_i, C_{pki}^{(l)})$ exists and $\mathcal{A}$ has issued $\mathcal{O}_{EXT}(pk_j)$.
 - $\mathcal{O}_{RE-Enc}(pk_i, pk_j, C_{pki}^{(l)})$: $\mathcal{C}$ responds as in Phase1 except a challenge derivative $(pk_i, C_{pki}^{(l)})$ exists and $\mathcal{A}$ has issued $\mathcal{O}_{EXT}(pk_j)$.
 - $\mathcal{O}_{DEC}(pk_i, C_{pki}^{(l)})$: If $(pk_i, C_{pki}^{(l)})$ is not a challenge derivative, $\mathcal{C}$ responds as in Phase1.
- Guess: Finally, $\mathcal{A}$ outputs a guess $b' \in \{0, 1\}$. $\mathcal{A}$ wins if $b' = b$.

We define adversary $\mathcal{A}$'s advantage in attacking PRE as $\text{Adv}_{\mathcal{A}} = |\Pr[b = b'] - 1/2|$

2.3 Reviews of Wang-Multi-Use-PRE scheme

Here we review a PRE scheme proposed by Wang et al. in CCS'09 poster session. Let 1^k be the security parameter, (q, g, G_1, G_T, e) be generated by a bilinear group generator with input (1^k) , and $\text{Sig} = (\mathcal{G}, \mathcal{S}, \mathcal{V})$ be a strongly unforgeable signature scheme. Let g_1, h_1, h_2 , and h_3 be four random elements in $G_1 \setminus \{g\}$. Furthermore, let $H_1: \{0, 1\}^* \rightarrow \mathbb{Z}_q^*$ and $H_2: G_T \rightarrow G_1$ be two one-way, collision-resistant cryptographic hash functions. The public parameters are: par

$= (q, g, g_1, h_1, h_2, h_3, G_1, G_T, e, \text{Sig}, H_1, H_2)$. Wang-Multi-Use-PRE scheme consists of the following five algorithms (KeyGen, Enc, RKGen, ReEnc, Dec):

- **KeyGen**(1^k) $\rightarrow (pk, sk)$: Selects $x \in_R \mathbb{Z}_q^*$, set $pk = g^x$, and $sk = x$.
- **Enc**(pk, m) $\rightarrow C_{pk}^{(l)}$: Given $m \in G_T$, selects $r \in_R \mathbb{Z}^*$, outputs a first-level ciphertext $C_{pk}^{(l)} = (c_{1,1}, c_{1,2}, c_{1,3}) = (g^r, m \cdot e(g_1, pk)^r, (h_1^{H_1(c_{1,1})} h_2^{H_1(c_{1,1} \| c_{1,2})} h_3)^r)$.
- **ReKeyGen**(sk_i, pk_j) $\rightarrow rk_{i \rightarrow j}$ ($i \neq j$): To generate a re-encryption key from pk_i to pk_j for pk_i 's proxy P_i , do the following:
 1. Select $r_{ij} \in_R \mathbb{Z}^*, K_{ij} \in_R G_T$.
 2. Compute $R_1^{(ij)} = g^{r_{ij}}, R_2^{(ij)} = K_{ij} \cdot e(g_1, pk_j)^{r_{ij}}, R_3^{(ij)} = sk_{P_i}, R_4^{(ij)} = (h_1^{H_1(R_1^{(ij)})} h_2^{H_1(R_1^{(ij)} \| R_2^{(ij)} \| R_3^{(ij)})} h_3)^{r_{ij}}, R_5^{(ij)} = H_2(K_{ij}) \cdot g_1^{-xi}$, where sk_{P_i} is a publicly available verification key of pk_i 's proxy P_i .
 3. Output $rk_{i \rightarrow j} = (R_1^{(ij)}, R_2^{(ij)}, R_3^{(ij)}, R_4^{(ij)}, R_5^{(ij)})$. The re-encryption key is sent to P_i via a secure channel.
- **ReEncrypt**($rk_{i \rightarrow j}, C_{pk_i}^{(l)}$) $\rightarrow C_{pk_j}^{(l+1)}$ ($i \neq j, l \geq 1$):
 1. To re-encrypt a First-level ciphertext denoted by $C_i^{(1)}$, do:
 - (a) Parse $C_i^{(1)}$ as $(c_{1,1}, c_{1,2}, c_{1,3})$, and $rk_{i \rightarrow j}$ as $(R_1^{(ij)}, R_2^{(ij)}, R_3^{(ij)}, R_4^{(ij)}, R_5^{(ij)})$.
 - (b) Check if $e(g, c_{1,3}) = e(c_{1,1}, h_1^{H_1(c_{1,1})} h_2^{H_1(c_{1,1} \| c_{1,2})} h_3)$ and $e(g, R_4^{(ij)}) = e(R_1^{(ij)}, (h_1^{H_1(R_1^{(ij)})} h_2^{H_1(R_1^{(ij)} \| R_2^{(ij)} \| R_3^{(ij)})} h_3))$ hold. If either of them fails, return $\perp$.
 - (c) Compute $C = (c'_{1,1}, c'_{1,2}, c'_{1,3}, c'_{2,1}, c'_{2,2}, c'_{2,3}, c'_{2,4})$, where $c'_{1,1} = c_{1,1}, c'_{1,2} = c_{1,2} \cdot e(c_{1,1}, R_5^{(ij)}), c'_{1,3} = c_{1,3}, c'_{2,1} = R_1^{(ij)}, c'_{2,2} = R_2^{(ij)}, c'_{2,3} = R_3^{(ij)}, c'_{2,4} = R_4^{(ij)}$.
 - (d) Let P_i be pk_i 's proxy, and ssk_{P_i} be the signing key of P_i corresponding to P_i 's verification key $R_4^{(ij)}$.
 - (e) Run the signing algorithm $S(ssk_{P_i} C)$, to generate a signature on the ciphertext tuple $(c'_{1,1}, c'_{1,2}, c'_{1,3}, c'_{2,1}, c'_{2,2}, c'_{2,3}, c'_{2,4})$, and denote the signature as $S_i^{(1)}$.
 - (f) Output the ciphertext $C_j^{(2)} = \langle C, S_i^{(1)} \rangle$.
 2. To re-encrypt a l^{th} - level ($l > 1$) ciphertext $C_i^{(l)}$:
 - (a) Parse $C_i^{(l)}$ as $(c_{1,1}, \dots, c_{l,1}, c_{l,2}, c_{l,3}, c_{l,4}, c_{l,5})$, and $rk_{i \rightarrow j}$ as $(R_1^{(ij)}, R_2^{(ij)}, R_3^{(ij)}, R_4^{(ij)}, R_5^{(ij)})$.
 - (b) Check if $e(g, c_{l,3}) = e(c_{l,1}, h_1^{H_1(c_{l,1})} h_2^{H_1(c_{l,1} \| c_{l,2})} h_3)$ and $e(g, R_4^{(ij)}) = e(R_1^{(ij)}, (h_1^{H_1(R_1^{(ij)})} h_2^{H_1(R_1^{(ij)} \| R_2^{(ij)} \| R_3^{(ij)})} h_3))$ hold. If either of them fails, return $\perp$.
 - (c) For $\forall k \in [2, l]$, check $\forall (c_{k,3}, c_{k,5}, (c_{1,1}, \dots, c_{k,1}, c_{k,3}, c_{k,4})) = 1$. Whenever one of the m fails, return $\perp$. Otherwise, do the following:
 - (d) Compute $C = (c'_{1,1}, \dots, c'_{l,1}, c'_{l,2}, c'_{l,3}, c'_{l,4}, c'_{l,5}, c'_{l+1,1}, c'_{l+1,2}, c'_{l+1,3}, c'_{l+1,4})$, where $c'_{l,2} = c_{l,2} \cdot e(c_{l,1}, R_5^{(ij)}), c'_{l+1,1} = R_1^{(ij)}, c'_{l+1,2} = R_2^{(ij)}, c'_{l+1,3} = R_3^{(ij)}, c'_{l+1,4} = R_4^{(ij)}$, and all other elements remain unchanged.
 - (e) Let P_i be pk_i 's proxy, and ssk_{P_i} be the signing key of P_i corresponding to P_i 's verification key $R_3^{(ij)}$.
 - (f) Run the signing algorithm $S(ssk_{P_i} C)$ to generate a signature on the ciphertext tuple $(c'_{1,1}, \dots, c'_{l,1}, c'_{l,2}, c'_{l,3}, c'_{l,4}, c'_{l,5}, c'_{l+1,1}, c'_{l+1,2}, c'_{l+1,3}, c'_{l+1,4})$, and denote the signature as $S_i^{(l)}$.
 - (g) Output the ciphertext $C_j^{(l+1)} = \langle C, S_i^{(l)} \rangle$.

- Decrypt($sk_i, C_{pki}^{(l)}$) $\rightarrow m$: If $C_{pki}^{(l)}$ can not be parsed as $(c_{1,1}, c_{1,2}, c_{1,3})$ for a first-level ciphertext, or $(c_{1,1}, \dots, c_{l,1}, c_{l,2}, c_{l,3}, c_{l,4}, c_{l,5})$ for an l^{th} - level ciphertext ($l > 1$), then re-turn $\perp$. Otherwise, continue the following process:
 1. For a First-level ciphertext,
 - (a) Verify that $e(g, c_{1,3}) = e(c_{1,1}, h_1^{H_1(c_{1,1})} h_2^{H_1(c_{1,1} \| c_{1,2})} h_3)$. If not, return $\perp$.
 - (b) Otherwise, compute $m \leftarrow c_{1,2} / e(c_{1,1}, g^{ski})$.
 - (c) Output m .
 2. For a l^{th} - level ($l > 1$) ciphertext ($l > 1$),
 - (a) Check if $e(g, c_{l,4}) = e(c_{l,1}, h_1^{H_1(c_{l,1})} h_2^{H_1(c_{l,1} \| c_{l,2} \| c_{l,3})} h_3)$. If not, return $\perp$. Otherwise:
 - (b) For $\forall k \in [2, l]$, check $\forall (c_{k,3}, c_{k,5}, (c_{1,1}, \dots, c_{k,1}, c_{k,3}, c_{k,4})) = 1$. Whenever one of them fails, return $\perp$. Otherwise, do the following:
 - (c) Compute $K_{l-1} \leftarrow c_{l,2} / e(c_{l,1}, g_1^{ski})$.
 - (d) For i from $l-2$ down to 1, compute $K_i \leftarrow c_{i+1,2} / e(c_{i+1,1}, H_2^{(Ki+I)})$.
 - (e) Compute $m \leftarrow c_{1,2} / e(c_{1,1}, H_2^{(K1)})$.
 - (f) Output m .

3. An Improvement For Wang-Multi-Use-PRE to Resist Zhang's Attack

Jindan Zhang and Xu An Wang [18] show Wang-Multi-Use-PRE is not CCA-secure in the corresponding security models in INCoS 2012. In this section, we describe Zhang's attack and propose an improvement for Wang-PRE to resist Zhang's attack.

According to Zhang's attack, let $C^* = C_*^{(1)} = (C_*^{(1)(1,1)}, C_*^{(1)(1,2)}, C_*^{(1)(1,3)}) = (g^{r^*,b}, m_b \cdot e(g_1, pk^*)^{r^*,b}, (h_1^{H_1(c_{*,b}^{(1)(1,1)})} h_2^{H_1(c_{*,b}^{(1)(1,1)} \| c_{*,b}^{(1)(1,2)})} h_3)^{r^*,b})$, an adversary $\mathcal{A}$ can malformed it's 2^{th} - level ciphertext $C_j^{(2)}$ for pk_j as below:

1. Issue $\mathcal{O}_{Re-EXT}(pk^*, pk_j)$, get $rk_{* \rightarrow j}$.
2. Choose $t \in_R \mathbb{Z}_q^*$, compute $C_j^{(2)(1,1)} = C_*^{(1)(1,2)} \cdot g^t = g^{r+t}$.
3. Compute $C_j^{(2)(1,2)} = C_*^{(1)(1,2)} \cdot e(g_1^t, pk^*) \cdot e(C_*^{(1)(1,1)} \cdot g^t, rk_{* \rightarrow j}^{(5)}) = m_b \cdot e(g^{r+t}, H_2(K))$.
4. Compute other part of $C_j^{(2)}$ as ReEncrypt algorithm.
5. Issue $\mathcal{O}_{DEC}(pk_j, C_j^{(2)})$, get plaintext m_b .

Because adversary $\mathcal{A}$ can crack the proxy P_{*j} , get the re-encryption key $rk_{* \rightarrow j}$ and the signing key ssk_{P_i} corresponding to P_i 's verification key $R_3^{(ij)}$. Then it can sign the ciphertext as proxy P_i , so the challenger cannot distinguish the malformed re-encryption from normal one. Since $C_j^{(2)} \neq \mathcal{O}_{RE-Enc}(pk^*, pk_j, C_*^{(1)})$, challenger $\mathcal{C}$ responds the query $\mathcal{O}_{DEC}(pk_j, C_j^{(2)})$, and outputs plaintext m to adversary $\mathcal{A}$.

But this problem can be solved simply by adding source $c_{1,2}$ in re-encryption ciphertext, and checking $e(g, c_{1,3}) = e(c_{1,1}, h_1^{H_1(c_{1,1})} h_2^{H_1(c_{1,1} \| c_{1,2})} h_3)$ before decrypting. The algorithm is modified as follows:

- In the section of the origin Algorithm: $\text{ReEncrypt}(rk_{i \rightarrow j}, C_{pki}^{(l)}) \rightarrow C_{pkj}^{(l+1)}$ ($i \neq j, l \geq 1$):
 1. To re-encrypt a First-level ciphertext $C_i^{(l)}$, denoted by $C_i^{(1)}$, on the (c) step: add source $c_{1,2}$ into the ciphertext. Compute $C = (c'_{1,1}, c'_{1,2}, c''_{1,2}, c'_{1,3}, c'_{2,1}, c'_{2,2}, c'_{2,3}, c'_{2,4})$, where $c''_{1,2} = c_{1,2}$, other values computed like in the origin Algorithm.
 2. To re-encrypt a l^{th} -level ($l > 1$) ciphertext $C_i^{(l)}$, on the (d) step: compute $C = (c'_{1,1}, \dots, c'_{l,1}, c'_{l,2}, c''_{l,2}, c'_{l,3}, c'_{l,4}, c'_{l+1,1}, c'_{l+1,2}, c'_{l+1,3}, c'_{l+1,4})$, where $c''_{l,2} = c_{l,2}$.
- In the section of the origin Algorithm: $\text{Decrypt}(sk_i, C_{pki}^{(l)}) \rightarrow m$:

2. For a l^{th} -level($l>1$) ciphertext($l>1$) , change the (a) step as: For $\forall k \in [1, l]$, check if $e(g, c_{k,4}) = e(c_{k,1}, h_1^{H_1(c_{k,1})} h_2^{H_1(c_{k,1} \| c_{k,2} \| c_{k,3})} h_3)$. If not, return $\perp$. Otherwise do the following steps in the origin Algorithm.

4. Proxy Bypass Attack

The PRE scheme allows a proxy to transform a ciphertext encrypted under A's public key into ciphertext that can be decrypted by B's secret key. Most of PRE schemes replace Alice's encrypt factor by the temp security value χ , then encrypt χ with B's public key. B could get χ by decrypt encrypted(χ) with its private key, then decrypt re-encrypted ciphertext with χ . We argue that with a view to chosen ciphertext security, such method may be suitable for single-hop schemes but it cannot fit for multi-use schemes.

The multi-use schemes allow re-encrypting from A to B, then re-encrypt the result from B to C and go on. Once C decrypts a re-encrypt ciphertext from A to B to C, it can get all the temp security values and decrypt other re-encrypted ciphertexts from A to B without proxy. We name this attack as proxy bypass attack. Wang-multi-use PRE scheme has such flaw and is vulnerable to the proxy bypass attack eventhough it has been improved by us.

We give a concrete attack of proxy bypass on Wang-multi-use PRE scheme and then discuss this flaw. This flaw also exists in some other multi-use scheme.

4.1 The Proxy Bypass Attack To Wang-Multi-Use-PRE

In this subsection, we indicate how a polynomial time adversary $\mathcal{A}$ can break the chosen ciphertext security of wang-multi-use-PRE scheme. Adversary $\mathcal{A}$ works as follows:

1. In Setup Phase, adversary $\mathcal{A}$ obtains the public parameters params from the challenger $\mathcal{C}$.
2. In Phase1 , adversary $\mathcal{A}$ issues queries below:
 - (a) $\mathcal{O}_{KeyGen}(i_A)$: $\mathcal{A}$ gets A's public key pk_A .
 - (b) $\mathcal{O}_{KeyGen}(i_B)$: $\mathcal{A}$ gets B's public key pk_B .
 - (c) $\mathcal{O}_{EXT}(pk_B)$: $\mathcal{A}$ gets B's private key sk_B .
3. In Challenge Phase, adversary $\mathcal{A}$ returns a challenged public key $pk^* = g^{x^*}$, and two equal-length plaintexts m_0, m_1 . Then challenger $\mathcal{C}$ picks $b \in_R \{0, 1\}$, sets the challenge ciphertext to $C_{*,b}^{(1)} = \text{Encrypt}(pk^*, m_b)$, and gives $C^* = C_{*,b}^{(1)} = (C_{*,b}^{(1)(1,1)}, C_{*,b}^{(1)(1,2)}, C_{*,b}^{(1)(1,3)})$ to $\mathcal{A}$. According to the proposed scheme, $C_{*,b}^{(1)}$ is of the following form: $C_{*,b}^{(1)(1,1)} = g^{r_{*,b}^*}$, $C_{*,b}^{(1)(1,2)} = m_b \cdot e(g_1, pk^*)^{r_{*,b}^*}$, and $C_{*,b}^{(1)(1,3)} = (h_1^{H_1(c_{*,b}^{(1)(1,1)})} h_2^{H_1(c_{*,b}^{(1)(1,1)} \| c_{*,b}^{(1)(1,2)})} h_3)^{r_{*,b}^*}$.
4. In Phase 2, adversary $\mathcal{A}$ performs the following steps:
 - (a) Adversary $\mathcal{A}$ selects a plaintext m_2 , computes $C_{*,2}^{(1)} = \text{Encrypt}(pk^*, m_2) = (g^{r_{*,2}^*}, m_2 \cdot e(g_1, pk^*)^{r_{*,2}^*}, (h_1^{H_1(c_{*,2}^{(1)})} h_2^{H_1(c_{*,2}^{(1)} \| c_{*,2}^{(1)})} h_3)^{r_{*,2}^*})$.
 - (b) Adversary $\mathcal{A}$ issues queries $\mathcal{O}_{RE-Enc}(pk^*, pk_A, C_{*,2}^{(1)})$, gets $C_{A,2}^{(2)} = (g^{r_{*,2}^*}, m_2 \cdot e(g^{r_{*,2}^*}, H_2(K_{*,A})), (h_1^{H_1(c_{*,2}^{(1)})} h_2^{H_1(c_{*,2}^{(1)} \| c_{*,2}^{(1)})} h_3)^{r_{*,2}^*}, R_1^{(*A)} = g^{r_{*,2}^* A}, R_2^{(*A)} = K_{*,A} \cdot e(g_1, pk_A)^{r_{*,2}^* A}, R_3^{(*A)}, R_4^{(*A)}, S_{*,A,2}^{(1)})$.
 - (c) Adversary $\mathcal{A}$ issues querie $\mathcal{O}_{RE-Enc}(pk_A, pk_B, C_{A,2}^{(2)})$, gets $C_{B,2}^{(3)} = (g^{r_{*,2}^*}, m_2 \cdot e(g^{r_{*,2}^*}, H_2(K_{*,A})), (h_1^{H_1(c_{*,2}^{(1)})} h_2^{H_1(c_{*,2}^{(1)} \| c_{*,2}^{(1)})} h_3)^{r_{*,2}^*}, R_1^{(*A)}, K_{*,A} \cdot e(g^{r_{*,2}^* A}, H_2(K_{AB})), R_3^{(*A)}, R_4^{(*A)}, S_{*,A,2}^{(1)}, R_1^{(AB)} = g^{r_{AB}}, R_2^{(AB)} = K_{AB} \cdot e(g_1, pk_B)^{r_{AB}}, R_3^{(AB)}, R_4^{(AB)}, S_{AB,2}^{(2)})$. While $\mathcal{A}$ has the private key sk_B , but because of $C_{*,2}^{(1)} \neq C_{*,b}^{(1)}$, so according to the security model, it is legal for $\mathcal{A}$ to issue this query.

- (d) $\mathcal{A}$ computes $K_{AB} \leftarrow C_{B,2}^{(3)(3,2)}/e(C_{B,2}^{(3)(3,1)}, g_1^{sk_B})$, then computes $K_{*A} \leftarrow C_{B,2}^{(3)(2,2)}/e(C_{B,2}^{(3)(2,1)}, H_2(K_{AB}))$.
- (e) $\mathcal{A}$ issues query $\mathcal{O}_{RE-Enc}(pk^*, pk_A, C_{*b}^{(1)})$, gets $C_{A,b}^{(2)} = (g^{r_{*,b}}, m_b \cdot e(g^{r_{*,b}}, H_2(K_{*A})), (h_1^{H_1(c_{1,1})} h_2^{H_1(c_{1,1} \| c_{1,2})} h_3)^{r_{*,b}}, R_1^{(*A)} = g^{r_{*A}}, R_2^{(*A)} = K_{*A} \cdot e(g, pk_A)^{r_{*A}}, R_3^{(*A)}, R_4^{(*A)}, R_{*A,b}^{(1)})$. Note that since $\mathcal{A}$ doesn't have the private key sk_A , according to the security model, it is legal for $\mathcal{A}$ to issue this query.
- (f) With K_{*A} , $\mathcal{A}$ computes $m_b \leftarrow C_{A,b}^{(2)(1,2)}/e(C_{A,b}^{(2)(1,1)}, H_2(K_{*A}))$.
5. Guess: With m_b , adversary $\mathcal{A}$ can certainly win the game.

4.2 Discussions

In previous subsection, we have indicated that wang-multi-use-PRE is insecure. The flaw exists in the ReEncrypt period. It converts a ciphertext encrypted by pk_i to a ciphertext encrypted by temp value K_{ij} , which is chosen by ReKeyGen and remains unchanged in every ReEncrypt time. In single-hop scheme, Once $\mathcal{A}$ gets the private key of j , it cannot get the re-encryption key $rk_{i \rightarrow j}$ or the re-encryption ciphertext of C^* for j . So $\mathcal{A}$ cannot get either temp value K_{*j} or the ciphertext encrypted by K_{*j} . But to a multi-use one, as long as $\mathcal{A}$ doesn't have a path from $C^{*(1)}$ to $C^{*(j)}$, $\mathcal{A}$ can get all the temp values K_{ij} in the path. So $\mathcal{A}$ has both temp value K_{*1} and the ciphertext encrypted by K_{*1} . This flaw is not only in wang-multi-use-PRE, but also exists in other multi-use schemes [5, 7, 13].

5. Conclusions

Wang, *et al.*, [12, 13] proposed a unidirectional and multi-use IND-CCA2 secure PRE scheme, claim that they solve the problem of constructing a unidirectional and multi-use IND-CCA2 secure PRE scheme [4, 7]. But Zhang, *et al.*, [18, 19] have shown their proposal is not CCA-secure by giving a concrete attack.

We first propose an improvement for Wang-Multi-Use-PRE to resist Zhang's attack. Zhang cracks the proxy, and gets the corresponding signing key. Then it can malformed the re-encryption ciphertext and cheats the Decrypt Oracle to decrypt the malformed ciphertext. This article fixes this problem by enhancing the public verifiability of the re-encrypted ciphertext. So the challenger can distinguish the malformed re-encryption ciphertext from normal one.

Secondly, we underline the difference between single-hop scheme and multi-use scheme, and present proxy bypass attack against multi-use IND-CCA secure PRE. Most multi-use PRE schemes do not randomize encrypt key in re-encrypt algorithm. Their IND-CCA security can be broken by this attack. We prove this flaw by attacking wang-multi-use-PRE.

Since Wang-Multi-Use-PRE is not CCA-secure, the problem of finding a multi-use CCA-secure PRE scheme deserves more efforts to study carefully. We should find a effective solution to avoid the proxy bypass attack in the next stage. Another problem is that Wang's proposal scheme features a linear ciphertext size. How to design more efficient scheme to reduce ciphertext size explosion is worth of study.

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