DDos Attack against Proxy in PRE and PRS

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Abstract—In 1998, Blaze, Bleumer, and Strauss proposed new kind of cryptographic primitives called proxy re-encryption (PRE) and proxy re-signature (PRS) [2]. In proxy re-encryption, a proxy can transform a ciphertext computed under Alice’s public key into one that can be opened under Bob’s decryption key. In proxy re-signature, a proxy can transform a signature computed under Alice’s secret key into one that can be verified by Bob’s public key. In 2005, Ateniese et al proposed a few new re-encryption schemes and discussed its several potential applications especially in the secure distributed storage [6]. In 2006, they proposed another few proxy re-signature schemes and also discussed its several potential applications [7]. They predicated that proxy re-encryption and proxy re-signature will play an important role in our life. Since then, researchers are sparked to give new lights to this area. Many excellent schemes have been proposed, especially, the IEEE P1363.3 standard working group is establishing the standard for proxy re-encryption, which will certainly give new power on researching in cryptography.

Generally speaking, we can split the research area into two parts-proxy re-encryption part and proxy re-signature part. In proxy re-encryption area, besides the pioneering work [2], [6], researchers have done some good work on achieving CCA2 proxy re-encryption such as [11], [22], some good work on achieving proxy re-encryption in identity-based settings [14] or between identity-based setting and PKI setting [9], [15], some good work on achieving proxy re-encryption without random oracle [16], [17], some good work on other aspects of proxy re-encryption [12], [18]–[21], [23], [24]. In proxy re-signature area, some good work also has been done [7], [13], [26], [27].

Motivation. Undoubtedly security is the most important thing when we consider on re-cryptography, but we can not ignore the practice of this new cryptographic primitive either. But in the current literature, very little attention has been paid on efficiency, especially on the efficiency of proxy. Because in most circumstances the semi-trusted proxies are relative scarce equipments, we are certain that they are easily suffering from the DDos attacking, especially when the proxy must implement lots of computation. We can find the proof in the [6]:

Our server is able to sustain 100 re-encryptions/sec until reaching about 1,000 outstanding requests. The server coped with up to 10,000 outstanding re-encryption requests, but quickly spiraled downwards thereafter.

So we must count the DDos attack in re-cryptography, at least decrease the dangerous caused by this attack.

Our Contribution. In this paper, we pay attention to the efficiency of the proxy. The workload of proxy can be divided into two parts: one part for checking the initial-signature or initial-ciphertext validity and the other part for proxy re-encryption or proxy re-signature. Most of existing schemes relying on bilinear pairings, which can be used to construct many interesting protocols [28]. We
revisit the literature on proxy re-encryption and proxy re-signature, especially pay attention on their ability of resisting DDos attacking, we propose a solution to decrease the dangerous of DDos attack on proxy. Also we give a new efficient proxy re-encryption scheme which can achieve CCA2 secure based on Cramer-Shoup encryption scheme and prove its security. We point out this is the most efficient proxy re-encryption schemes for the proxy which can achieve CCA2 secure in the literature.

We organize our paper as following: In section 2, we revisit the current literature on proxy re-encryption, especially on the efficiency of proxy, and give some comparisons to the existing schemes; In section 3, we revisit the current literature on proxy re-signature, especially on the efficiency of proxy, and also give some comparisons to the existing schemes; In section 4, we propose a solution to decrease the dangerous caused by DDos attack; In section 5, we give a new efficient proxy re-encryption scheme which can achieve CCA2 secure based on Cramer-Shoup encryption scheme and prove its security; In section 6, we give our concluding remarks.

II. REVISIT PROXY RE-ENCRYPTION SCHEMES

In this section, we revisit most known proxy re-encryption schemes in the literature, including traditional public key encryption environment, identity-based proxy re-encryption environment and hybrid encryption environment.

A. Proxy Re-encryption in Public Key Certificates Setting

1) [AFGH05 Scheme]: This Elgamal based scheme operates on bilinear parings in group \( G_1, G_2, G_T \).

1) Key Generation \((KG)\): A user \( A \)'s key pair is of the form \( pk_A = (z^{a_1}, z^{a_2}), sk_A = (a_1, a_2) \).

2) Re-Encryption Key Generation \((RG)\): A user \( A \) delegates to \( B \) by publishing the re-encryption key \( rk_{AB} = g_1^{a_1b_2} \in G_1 \), computed from \( B \)'s public key.

3) First-Level Encryption \((E_1)\): To encrypt a message \( m \in G_2 \) under \( pk_A \) in such a way that it can only be decrypted by the holder of \( sk_A \), output \( c_{a_1} = (Z^{a_1k}, mZ^k) \).

4) Second-Level Encryption \((E_2)\): To encrypt a message \( m \in G_2 \) under \( pk_A \) in such a way that it can be decrypted by \( A \) and her delegates, output \( c_{a_1r} = (g^k, mZ^{a_1k}) \).

5) Re-Encryption \((R)\): Any one can change a second-level ciphertext for \( A \) into a first-level ciphertext for \( B \) with \( rk_{AB} = g_1^{a_1b_2} \). From \( c_{a_1r} = (g^k, mZ^{a_1k}) \), compute \( e(g^k, g_1^{a_1b_2}) = Z^{b_2a_1k} \) and publish \( c_{b_2} = (Z^{b_2a_1k}, mZ^{a_1k}) = (Z^{b_2a_1k}, mZ^k) \).

6) Decryption \((D_1, D_2)\): To decrypt a first-level ciphertext \( c_a = (\alpha, \beta) \) with secret key \( sk = a \), compute \( m = \beta/\alpha^1/a \). To decrypt a second-level ciphertext \( c_a = (\alpha, \beta) \) with secret key \( sk = a \), compute \( m = \beta/e(\alpha, g)^1/a \).

In this scheme the delegation key need not be private. The scheme does not require initial ciphertext checking, but the proxy needs one pairing to do the re-encryption. This scheme has the property of containing two-level ciphertexts, some additional computation must be operated to distinguish the first level and second level. This scheme is not CCA2 secure.

We conclude this section with Table 1, which shows the efficiency of the proxy and the schemes’ ability of resisting DDos attack in public key certificate setting (Description of some schemes list in the appendix).

B. Proxy Re-encryption in Identity Based Setting

1) [M07b Scheme]: There are five entities involved in an identity-based proxy re-encryption system, delegator, proxy, delegatee, PKG and Re-encryption Key Generator, RKG. In this system, each of delegator and delegatee is an IBE user. The RKG generates re-encryption keys and sets them into the proxy via secure channel.

- The underlying IBE system (BB-IBE system):
  1) \( \text{Setup}_{IBE}(k) \): Given a security parameter \( k \), select a random generator \( g \in G \) and random elements \( g_1, g_2 \). Set \( g_1 = g, mk = g_2 \), and \( \text{parms} = (g, g_1, g_2, h) \). Let \( mk \) be the master secret key and let \( \text{parms} \) be the public parameters.
  2) \( \text{KeyGen}_{IBE}(mk, \text{parms}, ID) \): Given \( mk = g_2 \) and \( \text{ID} \) with \( \text{parms} \), pick a random \( u \in Z_p^* \). Set \( sk_{ID} = (d_0, d_1) = (g_2^u(g_1^h)^u, g^u) \).
  3) \( \text{Encrypt}_{IBE}(\text{ID}, \text{parms}, M) \): To encrypt a message \( M \in G_1 \) under the public key \( \text{ID} \in Z_p^* \), pick a random \( r \in Z_p^* \) and compute \( C_{ID} = (g^r, (g_1^h)^r, M/g_1^r) \in G^2 \times G_1 \).
  4) \( \text{DecKey}_{IBE}(sk_{ID}, \text{parms}, C_{ID}) \): Given ciphertext \( C_{ID} = (C_1, C_2, C_3) \) and the secret key \( sk_{ID} = (d_0, d_1) \) with \( \text{parms} \), compute \( M = C_3e(d_1, C_2)/e(d_0, C_1) \).

- The delegation system:
  1) \( \text{Encrypt}_{ID}(m, \text{parms}, ID') \): Given \( mk' \) with \( \text{parms} \), set \( sk_{B} = \).
  2) \( \text{KeyGen}_{RKG}(mk, \text{parms}) \): Given \( mk' = \) with \( \text{parms} \), set \( sk_{B} = \).
  3) \( \text{KeyGen}_{PBD}(sk_B, C_{ID}, \text{parms}, ID, ID') \): Given \( sk_B = \alpha, e_{ID} = g^u \) with \( \text{parms} \), set \( r_{KID \rightarrow ID'} = (ID \rightarrow ID', g^{u\alpha}) \).
  4) \( \text{ReEnc}_{ID'}(sk_{B}, C_{ID}, \text{parms}, C_{ID}, ID, ID') \): Given the delegator’s identity \( ID \), the delegatee’s identity \( ID' \), \( r_{KID \rightarrow ID'} = (ID \rightarrow ID', g^{u\alpha}), C_{ID} = (C_1, C_2, C_3) \) with \( \text{parms} \), re-encrypt the ciphertext \( C_{ID} \) into \( C_{ID'} \) as follows, \( C_{ID'} = (C_1', C_2', C_3') = (C_1, C_2, C_3e(C_{ID}' - ID', g^{u\alpha})) \in G^2 \times G_1 \).
  5) \( \text{Check}_{ID'}(sk_{B}, C_{ID}, ID) \): Given the delegator’s identity \( ID \) and \( C_{ID} = (C_1, C_2, C_3) \) with \( \text{parms} \), compute \( v_0 = e(C_1, g_1^h) \) and \( v_1 = e(C_2, g) \). If \( v_0 = v_1 \) then output 1. Otherwise output 0.
In this scheme, the proxy key needs not be private, checking the initial ciphertext needs two pairing computation and re-encryption needs one pairing computation. This scheme is CPA secure.

C. Proxy Re-encryption From CBE to IBE

1) [M07a Scheme]: The hybrid proxy re-encryption system involving the ElGamal-type CBE system and the BB-IBE system.

- The underlying IBE system (BB-IBE system):
  1) SetUpdate(k). Given a security parameter $k$, select a random generator $g \in G$ and random elements $g_2, h \in G$. Pick a random $\alpha \in \mathbb{Z}_p^*$. Set $g_1 = g^\alpha$, $mk = g_2^\alpha$, and $parms = (g_1, g_2, h)$. Let $mk$ be the master-secret key and let $parms$ be the public parameters.
  2) KeyGenIBE(mk, parms, ID). Given $mk = g_2^\alpha$ and $ID$ with $parms$, pick a random $u \in \mathbb{Z}_p^*$. Set $sk_{1ID} = (d_0, d_1) = (g_2^\alpha g_1^D u^\beta)^\alpha, g^u$.
  3) EncIBE(ID, parms, M). To encrypt a message $M \in G_1$ under the public key $ID \in \mathbb{Z}_p^*$, pick a random $r \in \mathbb{Z}_p^*$ and compute $C_{1ID} = (g', (g_1^D h)^r, Me(g_1, g_2)^r) \in G^2 \times G_1$.
  4) DecIBE(sk_{1ID}, parms, C_{1ID}). Given ciphertext $C_{1ID} = (C_1, C_2, C_3)$ and the secret key $sk_{1ID} = (d_0, d_1)$ with $parms$, compute $M = C_3 e(d_1, C_2)/e(d_0, C_1)$.

- The underlying CBE system (ElGamal-type CBE system):
  1) KeyGenCBE(k, parms). Given a security parameter $k$ and $parms$, pick a random $\beta, \theta, \delta \in \mathbb{Z}_p$. Set $g_{12} = g^\alpha g_1 = g_{11}^\beta$ and $g_3 = h^\delta$. The public key is $pk = (g_3, g_{12}, g_6)$. The secret random key is $sk = (\beta, \theta, \delta)$.
  2) EncCBE(pk, parms, M). Given $pk = (g_3, g_{12}, g_6)$ and a message $M$ with $parms$, pick a random $r \in \mathbb{Z}_p^*$ and compute $C_{PK} = (g_5, g_4, g_3, Me(g_1, g_2)^r) \in G^3 \times G_1$.
  3) DecCBE(sk, parms, C_{PK}). Given $C_{PK} = (C_1, C_2, C_3, C_4)$ and the secret key $sk = (\beta, \theta, \delta)$ with $parms$, compute $M = C_4 e(C_{12}^{\beta}, g_2)$.

- The delegation system:
  1) EGen(sk_{1ID}, parms). Given $sk_{1ID} = (d_0, d_1) = (g_2^\alpha g_1^D u^\beta)^\alpha, g^u$ for $ID$ with $parms$, set $e_{1ID} = d_1 = g^u$.
  2) KeyGenPRO(sk, e_{1ID}, parms). Given $sk = (\beta, \theta, \delta)$ and $e_{1ID} = g^u$ for $ID$ with $parms$, set $r_{kID} = (\beta, g^u/\theta, \delta)$.
  3) ReEnc(r_{kID}, parms, C_{PK}, ID). Given a CBE ciphertext $C_{PK} = (C_1, C_2, C_3, C_4)$, the re-encryption key $r_{kID} = (\beta, g^u/\theta, \delta)$ and $ID$ with $parms$, re-encrypt the ciphertext $C_{PK}$ into $C_{ID}$ as follows. $C_{1ID} = (C_1', C_2', C_3') = (C_1^{\beta}, C_2^{\beta}, C_3'(g^u/\theta, C_4^{1/\delta})) \in G^2 \times G_1$.
  4) Check(parms, C_{PK}, pk). Given $C_{PK} = (C_1, C_2, C_3, C_4)$ and $pk = (g_3, g_{12}, g_6)$ with $parms$, set $v_1 = e(C_1, g_4)$, $v_2 = e(C_2, g_3)$, $v_3 = e(C_3, g_4)$. If $v_1 = v_2$ and $v_3 = v_4$ then output 1, otherwise output 0.

In this scheme, the proxy key need be private, checking the initial ciphertext requires four pairing computation and re-encryption requires three exponentiation and one pairing computation. This scheme is IND-CPA secure and is being standardized by IEEE P1363.3 workgroup.

We conclude the above two sections with Table 2, which shows the efficiency of the proxy and the schemes’ ability of resisting DDoS attack in identity based setting (description of some schemes list in the appendix).

III. REVISIT PROXY RE-SIGNATURE SCHEMES

2) [AH06a Scheme]: This scheme based on the BLS short signature scheme. It requires a bilinear map $e : G_1 \times G_1 \rightarrow G_2$ operates over two groups $G_1, G_2$ of prime order $q$. The global parameters are $(e, q, G_1, G_2, g, H)$, where $g$ generates $G_1$ and $H$ is a hash function from arbitrary strings to elements in $G_1$.

1) KeyGeneration(KeyGen): On input the security parameter $1^k$, select a random $a \in \mathbb{Z}_q$, and...
output the key pair \( pk = g^a \) and \( sk = a \).

2) \( \text{Re} - \text{SignatureKeyGeneration(ReKey)}: \)

On input two secret keys \( sk_A = a, sk_B = b \) (the public keys are not required for this algorithm), output the resignature key \( rk_{A\rightarrow B} = b/a(\text{mod}q) \).

3) \( \text{Sign(Sign)}: \)

On input a secret key \( sk = a \) and a message \( m \), output \( \delta = H(m)^a \).

4) \( \text{Re} - \text{Sign(ReSign)}: \)

On input a re-signature key \( rk_{A\rightarrow B} \), a public key \( pk_A \), a signature \( \delta \), and a message \( m \), check that \( \text{Verify}(pk_A, m, \delta) = 1 \). If \( \delta \) does not verify, output \( 1 \); otherwise, output \( \delta' = \delta^{rk_{A\rightarrow B}} \).

5) \( \text{Verify(Verify)}: \)

On input a public key \( pk_A \), a message \( m \), and a purported signature \( \delta \), output 1 if \( e(\delta, g) = e(H(m), pk_A) \) and 0 otherwise.

In this scheme, the proxy key needs to be private, checking the initial signature requires one verifying, that is, two pairing computation. Re-signature requires one exponentiation computation. This scheme is EU-CMA secure.

We conclude this sections with Table 3, which shows the efficiency of the proxy and the signature schemes’ ability of resisting DDos attack.

### IV. A Solution to Decrease the Danger Caused by DDos Attack

Generally speaking, the workload of proxy can be divided into two parts, one part for the ciphertext or signature validity checking, one part for the re-encrypting or re-signing. We note that the validity checking can be done without any secret, but the re-encrypting or re-signing needs some secret to be done or at least needs to be done at some semi-trusted nodes. So we can separate the workload of the proxy into two parts. We introduce some aided proxies in the system, which can be some equipments having lots of computation power. But we do not plant any private value in it, all we need is these equipments can be trusted to honestly do the checking work. Furthermore, we denotes the original proxies as main proxies, which also must be powerful. It must do all the work of re-encryption or re-signature, and it must answer the re-encrypt or re-sign Oracle’s queries.

We also note the proxy re-encryption and proxy re-signature schemes can be divided by two kinds - one kind of proxy key must be private and the other need not - by the proxy key being private or not. In the case of proxy key being public, the difference between main proxies and aided proxies can be disappeared, that is to say, all the proxies run in the peer to peer model. In the case of proxy key being private, only the main proxies can do the re-encryption or re-signature work. We express our idea in Figure 1. In the figure, the white nodes denote the end user; the small black nodes denote the aided proxy which only do the checking work; the big black node denotes the main proxy which do the checking and re-encryption or re-signature work. The thin black arrows denote the communication from the end user to the aided proxy or main proxy; the big red arrows denote the communication from the aided proxy to the main proxy which only do the initial ciphertext or signature passing the checking. But we note that DDos attacking can not be avoided, all we can do is just decreasing the damage caused by it. So we remark our solution just tries best to...
resist the DDos attacking instead of avoiding it.

V. A NEW EFFICIENT RE-ENCRYPTION SCHEME BASED ON CRAMER-SHOUP ENCRYPTION AND ITS SECURITY PROOF

A. New Efficient Re-encryption Scheme Based on Cramer-Shoup Encryption

1) [Basic Cramer-Shoup Encryption]: The scheme assumes a group G of prime order q, where q is large. It also assumes that plaintext messages are (or can be encoded as) elements of G. It also uses a universal one-way family of hash functions that map long bit strings to elements of $Z_q$.

1) KeyGeneration. The key generation algorithm runs as follows. Random elements $g_1, g_2 \in G$ are chosen, and random elements $x_1, x_2, y_1, y_2 \in Z_q$ are also chosen. Next, the group elements $c = g_1^{x_1} g_2^{x_2}, d = g_1^{y_1} g_2^{y_2}, h = g_1^y$ are computed. Next, a hash function H is chosen from the family of universal one-way hash functions. The public key is $(g_1, g_2, c, d, h, H)$, and the private key is $(x_1, x_2, y_1, y_2, z)$.

2) Encryption. Given a message $m \in G$, the encryption algorithm runs as follows. First, it chooses $r \in Z_q$ at random. Then it computes $u_1 = g_1^r, u_2 = g_2^r, e = h^r m, \alpha = H(u_1, u_2, e), v = c^\epsilon d^\alpha$. The ciphertext is $(u_1, u_2, e, v)$.

3) Decryption. Given a ciphertext $(u_1, u_2, e, v)$, the decryption algorithm runs as follows. It first computes $\alpha = H(u_1, u_2, e)$, and tests if $u_1^{x_1 + y_1} u_2^{x_2 + y_2} \neq v$. If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs $m = e/u_1^\epsilon$.

2) [New Efficient Proxy re-encryption Scheme]: This scheme shares the same parameters and KeyGeneration algorithm with Cramer-Shoup scheme. The delegator’s public key is $pk_A = (g_1, g_2, c, d, h, H)$, his private key is $sk_A = (x_1, x_2, y_1, y_2, z)$; The delegatee’s public key is $pk_B = (g_1, g_2, c', d', h', H)$, his private key is $sk_B = (x_1', x_2', y_1', y_2', z')$.

1) Re- KeyGeneration(ReKeyGen) On input $sk_A = (x_1, x_2, y_1, y_2, z)$, $sk_B = (x_1', x_2', y_1', y_2', z')$, output the re-signature key $rk_{A\rightarrow B} = (k_x, k_x, k_y), k_{y2}, k_{x'}, k_{x'}, k_{y1}', k_{y2}', z/z'$. Where $k, k' \in Z_q^*$. The delegator preserves $k$ for ciphertext-transformation purpose and the delegatee preserves $k'$ for decryption purpose.

2) Encryption. Given a message $m \in G$, the encryption algorithm runs as follows. First, it chooses $r \in Z_q$ at random. Then it computes $u_1 = g_1^r, u_2 = g_2^r, e = h^r m, \alpha = H(u_1, u_2, e), v = c^\epsilon d^\alpha$. The ciphertext is $(u_1, u_2, e, v)$.

3) Ciphertext - transformation(CTran) On input initial ciphertext $(u_1, u_2, e, v)$, the delegator transforms it to be $(u_1, u_2, e, v')$ where $v' = v^k$.

4) Re- encryption(ReEnc) The proxy first verifies ciphertext $(u_1, u_2, e, v')$’s validity. If $u_1^{kx_2+k_1}, u_2^{kx_2+k_2 \neq v'}$ where $\alpha = H(u_1, u_2, e)$, then return "Reject", else computes $u_1' = u_1^{1/\epsilon}, u_2' = u_2^{1/\epsilon}, e' = e, \alpha' = H(u_1', u_2', e), v'' = u_1'^{k'x_2}/z' u_2'^{k'x_2}/z' u_1'k'y_1'/z' u_2'k'y_2'/z'$.\n
5) Decryption(Dec1). Given a re-encryption ciphertext $(u_1', u_2', e', v'')$, the decryption algorithm runs as follows. It first computes $\alpha' = H(u_1', u_2', e')$, and tests if $(u_1')^{k'x_2}/z' (u_2')^{k'x_2}/z' = v''$. If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs $m = e'/(u_1')^z$.

6) Decryption(Dec2). Given a normal ciphertext $(u_1, u_2, e, v)$, the decryption algorithm runs as follows. It first computes $\alpha = H(u_1, u_2, e)$, and tests if $(u_1)^{x_1 + y_1} (u_2)^{x_2 + y_2} = v$. If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs $m = e/(u_1)^z$.© 2013 ACADEMY PUBLISHER
First we show our re-encryption ciphertext is a valid Cramer-Shoup ciphertext.

\[
\begin{align*}
    u_1' &= u_1 z/z' = g_1^{r z/z'} = g_1^{r'} \\
    u_2' &= u_2 z/z' = g_2^{r z/z'} = g_2^{r'} \\
    e' &= e = h^r m = g_1^{z/z'} = (g_1^z)^{r z/z'} = (h^z)^{r z/z'} = (h')^{r'} \\
    a' &= H(u_1', u_2', e') \\
    v'' &= u_1 k' z/z' u_2 k' z/z' u_1 k' z z/z' u_2 k' z z/z' \\
        &= g_1^{k' z z/z'} g_2^{k' z z/z'} g_1^{k' z z/z'} g_2^{k' z z/z'} \\
        &= (e^{k'})^{y z/z'} (d^{k'})^{v z/z'} a' \\
        &= (e^{k'})^{y} (d^{k'})^{v} a' \\
        &= (e^{k'})^{r} (d^{k'})^{r} a'
\end{align*}
\]

Next we note that, in our scheme, the delegator must preserve \(k\), it has the Ciphertext-transformation algorithm which operated by delegator by \(k\), and the delegatee must preserve \(k'\) for validating the re-encryption ciphertext. Everything we do like that is just for CCA2 security, which we will explain in the next section. And we believe that ciphertext-transformation algorithm is a reasonable step for re-encryption, after all, re-encryption is possible only after the delegator agrees this. The additional cost is that delegator and delegatee must preserve \(k\) and \(k'\) for every re-key generation. This is a shortcoming which we hope it can be improved in the future.

At last, we compare our scheme with other CCA2 secure scheme. First, the proxy key in our scheme must be private, the initial ciphertext checking requires two exponentiation computation and the re-encryption requires six exponentiation computation. Because our scheme needs no pairing (one pairing almost equals six exponentiation), so our scheme’s proxy is most efficient so far, which can be seen in Table 4.

### B. Security Analysis

First we give our security model for our new proxy re-encryption scheme, we follow the models in [7], [11]. Then we prove our scheme in this model.

**Definition 1: (Bidirectional PRE-CCA game)** Let \(k\) be the security parameter. Let \(A\) be an oracle TM, representing the adversary. The game consists of an execution of \(A\) with the following oracles, which can be invoked multiple times in any order, subject to the constraints below:

- **Uncorrupted key generation** \(O_{\text{keygen}}\): Obtain a new key pair as \((pk, sk)\) \(\leftarrow KeyGen(1^k)\). \(A\) is given \(pk\).
- **Corrupted key generation** \(O_{\text{corkeygen}}\): Obtain a new key pair as \((pk, sk)\) \(\leftarrow KeyGen(1^k)\). \(A\) is given \(pk\) and \(sk\).
- **Re-encryption key generation** \(O_{\text{rekeygen}}\): On input \((pk, pk')\) by the adversary, where \(pk, pk'\) were generated before by \(KeyGen\), return the re-encryption key \(r_{pk, pk'} = ReKeyGen(sk, sk')\) where \(sk\) and \(sk'\) are the secret keys that correspond to \(pk\) and \(pk'\). We require that either both \(pk\) and \(pk'\) are corrupted, or alternatively both are uncorrupted. We do not allow for re-encryption key generation queries between a corrupted and an un-corrupted key. This represents the restriction that the identities of parties whose security is compromised should be fixed in advance.
- **Encryption oracle** \(O_{\text{ciphertext}}\): Given a message \(m \in G\), the output ciphertext is \((u_1, u_2, e, v)\).
- **Ciphertext-transformation oracle** \(O_{\text{extra}}\): On input ciphertext \((u_1, u_2, e, v)\), the delegator transforms it to \((u_1, u_2, e, v')\) where \(v' = v^k\).
- **Challenge oracle**: This oracle can be queried only once. On input \((pk^*, m_0, m_1)\), where \(pk^*\) is called the challenge key, the oracle chooses a bit \(b \leftarrow \{0, 1\}\) and returns the challenge ciphertext \(C^* = Enc(pk^*, m_b)\). (As we note later, the challenge key must be uncorrupted for \(A\) to win).
- **Re-encryption** \(O_{\text{enc}}\): On input \((pk, pk', C)\), where \(pk, pk'\) were generated before by \(KeyGen\), if \(pk'\) is corrupted, then return a special symbol \(\perp\) which is not in the domains of messages or ciphertexts. Else, return the re-encrypted ciphertext \(C' = ReEnc(ReKeyGen(sk, sk'), C)\).
- **Decryption oracle** \(O_{\text{dec}}\): On input a re-encryption ciphertext \((pk, C)\), if \(pk\) was not generated before by \(KeyGen\), then return a special symbol \(\perp\) which is not in the domain \(D\) of messages. Else, return \(Dec(sk, C)\).
- **Decision oracle**: This oracle can also be queried only once. On input \(b'\): If \(b' = b\) and the challenge key \(pk^*\) is not corrupted, then output 1; else output 0.

We say that \(A\) wins the \(PRE-CCA\) game with advantage \(\epsilon\) if the probability, over the random choices of \(A\) and the oracles, that the decision oracle is invoked and outputs 1, is at least \(1/2 + \epsilon\).

**Internal and External Security.** Our security model protects users from two types of attacks: those launched from parties outside the system (External Security), and those launched from parties inside the system, such as the proxy, another delegation partner, or some collusion between them (Internal Security). We now provide both intuition and a formalization of these security notions.

**External Security:** Our first security notion protects a user from adversaries outside the system (i.e., excluding the proxy and any delegation partners).

**Definition 2:** A PRE scheme is chosen-ciphertext se-
cure if the probability
\[
\Pr[(pk^*, sk^*) \leftarrow O_{\text{keygen}}(\lambda), \{pk_z, sk_z\} \leftarrow O_{\text{setkeygen}}(\lambda), \{(pk_h, sk_h) \leftarrow O_{\text{keygen}}(\lambda),\{R_{sh} \leftarrow O_{\text{Rekeygen}(sk_h, pk_h)}, \{R_{bh} \leftarrow O_{\text{Rekeygen}(sk_h, pk_h)}, \{R_{hx} \leftarrow O_{\text{Rekeygen}(sk_h, pk_h)}, \{R_{xx'} \leftarrow O_{\text{Rekeygen}(sk_h, pk_h)}, (m_0, m_1, St) \leftarrow A_{\text{keygen}, \text{setkeygen}, \text{O}_{\text{trans}}, \text{O}_{\text{tra}}}(pk^*,\{pk_z, sk_z\},\{pk_h\},\{R_{xx'}\},\{R_{sh}\},\{R_{bh}\},\{R_{hx}\},\{R_{xx'}\}), d^* \leftarrow \mathbb{Z} \setminus \{0,1\}, C^* = Enc_2(m_{\ast}, pk^*), d' \leftarrow A_{\text{trans}, \text{O}_{\text{tra}}}(C^*, St); d' = d^*]
\]

is negligibly close to 1/2 for any PPT adversary A. In our notation, St is a state information maintained by A while \((pk, sk)\) is the target user’s key pair generated by the challenger that also chooses other keys for corrupt and honest parties. For other honest parties, keys are subscripted by h or ‘h and we subscript corrupt keys by x or ‘x. The adversary is given access to all re-encryption keys but those that would allow re-encrypting from the target user to a corrupt one. In the game, A is said to have advantage \(\epsilon\) if this probability, taken over random choices of A and all oracles, is at least \(1/2 + \epsilon\).

**Internal Security:** Our second security notion protects a user, as much as possible, when they are fooled into trusting a rogue proxy and/or delegation partner (who may be colluding).

- **Limited Proxy:** If the delegator and the delegatee are both honest, then the proxy cannot decrypt the ciphertext or even distinguish two ciphertexts. We will show our scheme is CPA secure for the proxy.
- **Delegate Security:** Because in our scheme, the proxy key is private, then If the delegator and proxy collude, the delegatee is no longer safe.
- **Delegator Security:** As the same reason above, the delegator is no longer safe as the delegator and proxy collude in our scheme.

After we set the model for our scheme, we prove our scheme’s security. We give two theorems as following:

**Theorem 1:** Our proxy re-encryption scheme is secure against adaptive chosen ciphertext attack for the external adversaries assuming that (1) the hash function \(H\) is chosen from a universal one-way family, and (2) the Diffie-Hellman decision problem is hard in the group \(G\).

**Proof:** The intuition is that the initial ciphertext is a Cramer-Shoup ciphertext, nobody can get help from the re-encryption oracle by querying the oracle with "invalid ciphertext". Also our re-encryption ciphertext is a Cramer-Shoup ciphertext, nobody can get help either. The proxy key in our scheme is of the form \(r_{pk_{A \rightarrow B}} = (kz_1, kz_2, k_{y_1}, k_{y_2}, k_{z'}, k_{z''}, k_{z'''} z/z')\) any external adversary can not distinguish it with \(sk_A = (x_1, x_2, y_1, y_2, z), sk_B = (x_1', x_2', y_1', y_2', z')\), thus the adversary can not get any help information from Re-Keygeneration Oracle.

We give our scheme’s formal proof as following. Assume the external adversaries’ algorithm B breaking the IND-CCA2 property of the scheme, we use B to construct algorithm A distinguish a four tuple \((g_1, g_2, u_1, u_2)\) from G is a DHD tuple or not. Oracle queries from B are handled by A as following:

- **Query to Key Generation Oracle:** If user i is corrupted, \(A\) randomly chooses \(sk_i = (x_{i1}, x_{i2}, y_{i1}, y_{i2}, z_i) \in Z_q\) at random, also chooses a hash function \(H\) at random and computes \(pk_i = (g_1, g_2, c_i = g_1^{x_{i1}} g_2^{x_{i2}}, d_i = g_1^{y_{i1}} g_2^{y_{i2}}, h_i = g_i^{x_{i1}}, H)\), returns \(pk_i\) and \(sk_i\) to the adversary. If the user j is uncorrupted, \(A\) randomly chooses \(sk_j = (x_{j1}, x_{j2}, y_{j1}, y_{j2}, z_1, z_2) \in Z_q\) at random, also chooses a hash function \(H\) at random and computes \(pk_j = (g_1, g_2, c_j = g_1^{x_{j1}} g_2^{x_{j2}}, d_j = g_1^{y_{j1}} g_2^{y_{j2}}, h_j = g_i^{x_{j1}} g_2^{y_{j2}}, H)\), returns \(pk_j\) to the adversary. That is, there is a KeGen list of form.(corrupted, i, sk_i = (x_{i1}, x_{i2}, y_{i1}, y_{i2}, z_i), \(pk_i = (g_1, g_2, c_i = g_1^{x_{i1}} g_2^{x_{i2}}, d_i = g_1^{y_{i1}} g_2^{y_{i2}}, h_i = g_i^{x_{i1}}, H)\) or (uncorrupted, j, sk_j = (x_{j1}, x_{j2}, y_{j1}, y_{j2}, z_1, z_2), \(pk_j = (g_1, g_2, c_j = g_1^{x_{j1}} g_2^{x_{j2}}, d_j = g_1^{y_{j1}} g_2^{y_{j2}}, h_j = g_i^{x_{j1}} g_2^{y_{j2}}, H)\).

- **Query to Re-Keygeneration Oracle:** On input \((i, j)\) to \(O_{\text{Rekeygen}}\), if one of i and j is uncorrupted and the other is corrupted, then this call is illegal (So we just consider uncorrupted users in re-key generation, ciphertext-transformation, re-encryption and decryption oracle queries). Otherwise, \(A\) randomly chooses \(k_i, k_j, z \in Z_q\) and outputs the re-key encryption key \(r_{k_{i \rightarrow j}} = (k_{x_{i1}}, k_{x_{i2}}, k_{y_{i1}}, k_{y_{i2}}, k_{x_{j1}}, k_{x_{j2}}, k_{y_{j1}}, k_{y_{j2}}, z)\). That is, there is a ReEnc KeyGen list of form (uncorrupted, i, k_i, uncorrupted, j, k_j, z)

- **Query to Encryption Oracle:** Given a message \(m \in G\), the encryption algorithm runs as follows. First, it chooses \(r \in Z_q\) at random. Then it computes \(u_1 = g_1^r, u_2 = g_2^r, e = u_1^{z_1} u_2^{z_2}, m, \alpha = H(u_1, u_2, e), v = e^\alpha d^\alpha\). The ciphertext is \((u_1, u_2, e, v)\).

- **Query to Ciphertext-Transformation Oracle:** On input \((u_1, u_2, e, v)\) from user i to user j iif user i and j are uncorrupted, B search in the ReEncKeyGen list and if finding an item including i and j, then compute \(v' = v^b\), and outputs \((u_1, u_2, e, v')\), else first run the querying to Re-Keygeneration Oracle.

- **Query to the Re-encryption Oracle:** On input \((u_1, u_2, e, v')\) from user i to user j, search the ReEncKeyGen list and if finding an item including i and j, then B first verifies ciphertext \((u_1, u_2, e, v')\)’s validity. if \(u_1^{k_{x_{i1}}} u_2^{k_{x_{i2}}} u_1^{k_{y_{i1}}} u_2^{k_{y_{i2}}} = v'\) where \(\alpha = H(u_1, u_2, e)\), then return
"Reject", else computes $u_1^{*} = u_1^z, u_2^{*} = u_2^z, e' = e, \alpha' = H(u_1^{*}, u_2^{*}, e'), v'' = u_1^{*}k_{1}\cdot z_{u_2^{*}}\cdot k_{1}\cdot y_{1}\cdot \alpha'\cdot u_2^{*}k_{2}\cdot z_{u_2^{*}}\cdot \alpha'\cdot z_{u_2^{*}}$. If not finding such item, first run the querying to Re-Keygeneration Oracle and querying to Ciphertext-Transformation Oracle.

- **Query to the Decryptionlevel1 Oracle:** Level 1 ciphertext is the re-encryption ciphertext. On input $(u_1^{*}, u_2^{*}, e', v'')$ from user $i$ to $j$, $B$ first search ReEncKeyGen list and if finding an item including $i$ and $j$, then $B$ first verifies ciphertext $(u_1^{*}, u_2^{*}, e', e'')$’s validity, if $u_1^{*}k_{1}\cdot z_{u_2^{*}}\cdot k_{1}\cdot y_{1}\cdot \alpha'\cdot u_2^{*}k_{2}\cdot z_{u_2^{*}}\• \neq v''$, where $\alpha' = H(u_1^{*}, u_2^{*}, e')$, then returns "Reject", else computes $m = e'/u_1^{*}u_2^{*}$, if output $m$. If not finding such items, first run the querying to Re-Key generation Oracle, querying to Ciphertext-Transformation Oracle and Re-Encryption Oracle.

- **Query to the Decryptionlevel2 Oracle:** Level 2 ciphertext is the normal ciphertext. On input $e = (u_1, u_2, e, v)$ to user $j$, $B$ first computes $\alpha = H(u_1, u_2, e)$, and search the KeyGen list if finding an item including $i$ and uncorrupted then tests if $u_1^{*}y_{1}\cdot \alpha'\cdot u_2^{*}y_{2}\cdot \alpha'\cdot v = e$. If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs $m = e/u_1^{z}u_2^{z}$, if finding an item including $j$ and corrupted, run decen$(sk_{j}, e)$. Else first run query to Key Generation Oracle.

Next we show our oracle simulation is perfect.

- **Key Generation Oracle Simulation:** For corrupted users, the simulated output $(sk_{i} = (x_{i1}, x_{21}, y_{11}, y_{21}, z_{1}), pk_{i} = (g_{1}, y_{2}, c_{i} = g_{1}^{x_{i1}} z_{i} \cdot d_{i} = g_{2}^{y_{2}} z_{i}, h_{1} = g_{1}^{y_{2}}, H))$ is an identical distribution to the real distribution of real private key and public key. For uncorrupted users, assuming $g_{2} = g_{2}^{y_{2}}$ as the same technique used in Cramer-Shoup encryption, the simulated output $(sk_{j} = (x_{j1}, x_{j2}, y_{j1}, y_{j2}, z_{j1}, z_{j2}), pk_{j} = (g_{1}, y_{2}, c_{j} = g_{1}^{x_{j1}} z_{j1} \cdot d_{j} = g_{2}^{y_{2}} z_{j1}, h_{j} = g_{1}^{y_{2}} z_{j1}, H))$ is also an identical distribution to the real distribution of real private key and public key for $h_{j} = g_{1}^{y_{2}} z_{j1}$ and user $j$ being a DDH tuple, as the same technique used in Cramer-Shoup Encryption. Thus the real output and simulated output are indistinguishable. So this is also a perfect simulation.

- **Re-Keygeneration Oracle Simulation:** When user $i$ query the oracle with input $i, j$ and users $i$ or $j$ is corrupted, we call this query illegal and output $\bot$. If users $i$ and $j$ are uncorrupted, the simulated output is $rk_{i\rightarrow j} = (k_{i1}, k_{i2}, k_{i1}, k_{i2}, k_{j1}, k_{j2}, k_{j1}, k_{j2}, z)$ which is indistinguishable with $rk_{A\rightarrow B} = (k_{i1}, k_{i2}, k_{j1}, k_{j2}, k_{i1}, k_{i2}, k_{j1}, k_{j2}, z/z')$. So this is also a perfect simulation.

- **Encryption Oracle Simulation:** In the real encryption, Given a message $m \in G$, the encryption algorithm runs as follows. First, it chooses $r \in Z_{q}$ at random. Then it computes $u_1 = g_1^r, u_2 = g_2^e, h = h^m, \alpha = H(u_1, u_2, e), v = e^d r^\alpha$. The ciphertext is $(u_1, u_2, e, v)$. In our simulation, Given a message $m \in G$, the encryption algorithm runs as follows. First, it chooses $r \in Z_{q}$ at random. Then it computes $u_1 = g_1^r, u_2 = g_2^e, e = u_1^{z}m, \alpha = H(u_1, u_2, e), v = e^d r^\alpha$. The ciphertext is $(u_1, u_2, e, v)$. From Cramer-Shoup encryption, if $(g_1, g_2, u_1, u_2)$ is a DDH tuple, the two ciphertexts can not be distinguished. So this is also a perfect simulation.

- **Ciphertext-Transformation Oracle Simulation:** In the real ciphertext-transformation, on input initial ciphertext $(u_1, u_2, e, v)$, the delegator transforms it to be $(u_1, u_2, e, v')$ where $v' = v^k$. While in our oracle simulation, on input $(u_1, u_2, e, v)$, if user $i$ and user $j$ are uncorrupted, it computes $v' = v^{k^i}$, and outputs $(u_1, u_2, e, v^{k^i})$, this is indistinguishable from the real outputs $(u_1, u_2, e, v)$. If users $i$ or $j$ is corrupted, it outputs $\bot$. So this is also a perfect simulation.

- **Re-encryption Oracle Simulation:** In the real re-encryption, The proxy first verifies ciphertext $(u_1, u_2, e, v')$’s validity, if $u_1^{k_{x_{1}}+k_{y_{1}}\cdot \alpha} u_{2}^{k_{x_{2}}+k_{y_{2}}\cdot \alpha} \neq v'$ where $\alpha = H(u_1, u_2, e)$, then return "Reject", else computes $u_1^{'} = u_1^{z/2}, u_2^{'} = u_2^{z/2}, e' = e, \alpha' = H(u_1, u_2, e'), v'' = u_1^{k_{x_{1}}+k_{y_{1}}\cdot \alpha} u_{2}^{k_{x_{2}}+k_{y_{2}}\cdot \alpha}$. In our simulation, on input $(u_1, u_2, e, v)$, $B$ first verifies ciphertext $(u_1, u_2, e, v')$’s validity, if $u_1^{k_{x_{1}}+k_{y_{1}}\cdot \alpha} u_{2}^{k_{x_{2}}+k_{y_{2}}\cdot \alpha} \neq v'$, then return "Reject", else computes $u_1^{'} = u_1^{z/2}, u_2^{'} = u_2^{z/2}, e' = e, \alpha' = H(u_1, u_2, e'), v'' = u_1^{k_{x_{1}}+k_{y_{1}}\cdot \alpha} u_{2}^{k_{x_{2}}+k_{y_{2}}\cdot \alpha}$ output $(u_1^{'}, u_2^{'}, e', v'')$. In lemma 1, we will show anybody cannot construct valid $(u_1, u_2, e, v')$ by himself with $(g_1, g_2, u_1, u_2)$ being not a DDH tuple, as the same technique used in Cramer-Shoup Encryption. Thus the real output and simulated output are indistinguishable. So this is also a perfect simulation.

- **Decryptionlevel1 Oracle Simulation:** In the real Decryption Decen, Given a re-encryption ciphertext $(u_1^{'}, u_2^{'}, e', v'')$, the decryption algorithm runs as follows. First, it computes $\alpha' = H(u_1, u_2, e')$, and tests if $(u_1^{'})^{e'}(u_2^{'}+u_2^{'}+\alpha')^{(u_2^{'})^{k_{y_{1}}+k_{y_{2}}\cdot \alpha}$ $= v''$. If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs $m = e'/u_1^{*}u_2^{*}$, and in our simulation, on input $(u_1^{'}, u_2^{'}, e', v'')$, from user $i$ to $j$, $B$ first verifies ciphertext $(u_1^{'}, u_2^{'}, e', v'')$. If $u_1^{k_{x_{2}}+k_{y_{1}}\cdot \alpha} u_{2}^{k_{x_{2}}+k_{y_{2}}\cdot \alpha} \neq v''$, then returns "Reject", else computes $m = e'/u_1^{*}u_2^{*}$, and output $\bot$. As in Cramer-Shoup encryption, if $(g_1, g_2, u_1, u_2)$ is a DDH tuple, our simulated decryption is a perfect decryption. In lemma 1, we will show anybody cannot construct valid $(u_1^{'}, u_2^{'}, e', v'')$ by himself with $(g_1, g_2, u_1, u_2)$ being not a DDH tuple. Thus anybody cannot distinguish the real decryption and the simulated decryption.
this is also a perfect simulation.

- **DecryptionOracle Simulation:** In the real Decryption Dec_{c_2}, a normal ciphertext \((u_1, u_2, e, v)\), the decryption algorithm runs as follows. It first computes \(\alpha = H(u_1, u_2, e)\), and tests if \((u_1)^{x_1+y_1}\alpha (u_2)^{x_2+y_2} = v\). If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs \(m = e/u_1^x\). In our simulation, on input \(c = (u_1, u_2, e, v)\) to user \(j\), \(B\) first computes \(\alpha = H(u_1, u_2, e)\), and searches the KeyGen list if finding an item including \(j\) and uncorrupted then tests if \(u_1^{x_1+y_1}\alpha u_2^{x_2+y_2} = v\). If this condition does not hold, the decryption algorithm outputs "reject"; otherwise, it outputs \(m = e/u_1^x\) as in Cramer-Shoup encryption, if \((g_1, g_2, u_1, u_2)\) is a DDH tuple. Our simulated decryption is a perfect decryption. In Lemma 1, we will show anybody cannot construct valid \((u_1, u_2, e, v)\) by himself with \((g_1, g_2, u_1, u_2)\) being not a DDH tuple. Thus, anybody cannot distinguish the real decryption and the simulated decryption. So this is also a perfect simulation.

**Lemma 1:** If \((g_1, g_2, u_1, u_2)\) is not a DDH tuple, the decryption oracle (includes dec_{c_1}, dec_{c_2}, DecryptionOracle and DecryptionOracle Oracle) will reject all invalid ciphertexts, except with negligible probability.

**Proof:** The proof of this lemma is same as [1], the only difference is that in the dec_{c_1} and DecryptionOracle Oracle simulation, the adversary must solve the first three equations

\[
x_1 + w_2 = \log_{g_1} q \mod q
\]
\[
y_1 + w_2 = \log_{g_2} q \mod q
\]
\[
k_r x_1 + k_r \alpha y_1 + k w_2 x_2 + k w_2 \alpha y_2 = \log_{g_1} q \mod q
\]
\[
x_1 + w_2 = \log_{g_2} q \mod q
\]
\[
y_1 = \log_{g_2} q \mod q
\]
\[
r_1 x_1 + r_1 \alpha y_1 + w_2 x_2 + w_2 \alpha y_2 = \log_{g_1} q \mod q
\]

while in the dec_{c_1} and DecryptionOracle Oracle simulation, the adversary must solve the latter three equations. The above two equations are all have \(q\) solutions, thus the adversary can guess the right \(v\) is negligible. For full proof readers may refereed [1].

Thus, our simulation is perfect for the external adversary, if \(A\) can break our proxy re-encryption scheme, \(B\) can solve the DDH problem in \(G\). Thus we prove our theorem.

**Theorem 2:** Our proxy re-encryption scheme is secure against adaptive chosen plaintext attack for the proxy assuming that the DL problem is hard in the group \(G\).

**Proof:** For the proxy, our scheme just like a Elgamal proxy re-encryption scheme proposed by [2]. We know that scheme is CPA secure, so our scheme is CPA secure for the proxy.

**C. Efficiency**

We compare our scheme’s efficiency with other CCA proxy re-encryption schemes in Table 4. We know from [10] that one pairing almost equals six exponentiation, so our scheme is the most efficient until now which can achieve CCA2 secure.

**VI. Concluding Remarks**

In this paper, we introduce a new attack- DDos attack against proxy in the proxy re-cryptography. Although this attack can also be implemented against other cryptographic primitives, the danger caused by it in proxy re-cryptography seems more serious. We revisit the current literature, paying attention on their resisting DDos attack ability. We suggest a solution to decline the impact of DDos attacking. Also we give a new efficient proxy re-encryption scheme which can achieve CCA2 secure based on Cramer-Shoup encryption scheme and prove its security. We point out this is the most efficient proxy re-encryption schemes for the proxy which can achieve CCA2 secure in the literature until now. But we also note that our scheme is a bidirectional scheme with private re-encryption key, which maybe restrict its application. Finding a unidirectional re-encryption scheme with public re-encryption key and other good properties defined in [6] is still an open problem.

**References**


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<th>Checking</th>
<th>Re-encryption</th>
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Remark 4: * This is a RSA-TBOS signcryption with proxy re-encryption scheme, but this scheme have not the process checking initial ciphertext, any one can construct invalid ciphertext for DDos attacking, so it is not efficient for resisting DDos attacking.

Figure 5. Efficiency comparison between our scheme and other CCA2 secure schemes


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