Anonymous IBE From Quadratic Residue With Fast Encryption

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Abstract. We develop two variants of Cocks' identity-based encryption. One variant has faster encryption which is as efficient as RSA encryption. The other variant makes the first variant anonymous under suitable complexity assumptions, while its decryption efficiency is about twice lower than the first one. Both the variants have ciphertext expansion twice larger than the original Cocks' identity-based encryption.

Keywords: Public-key cryptography · identity-based encryption · Cocks' scheme · quadratic residuosity · anonymous encryption

1 Introduction

The notion of identity-based cryptography was first proposed by Shamir [14] in 1984. This new paradigm of cryptography aims at solving the issue of managing and recovering the public-key certificate by simplifying the key management. For example, users' identification information such as email addresses or names rather than digital certificates can be used as their public key for encrypting or verifying digital signature. Shamir constructed an identity-based signature scheme using the RSA function, but developing identity-based encryption (IBE) schemes turns out to be much harder. Until the year 2001, Shamir's open problem was solved by Boneh and Franklin [3] and Cocks [10] independently. Recently, lattice was considered as an emergent system for constructing IBE schemes [11]. The Boneh-Franklin IBE scheme makes use of bilinear maps and is truly practical. Therefore, this work has attracted tons of attention from researchers over the years. However, Cocks' IBE scheme received less attention because of the lack of algebraic structure. Although Cocks' IBE scheme is inefficient for large messages, it is simple, elegant and secure under the standard quadratic residuosity (QR) assumption in the random oracle model. It can be used to encrypt short session keys in practice, e.g., a 128-bit symmetric key. Thus, the scheme was followed up by some researchers [1, 4, 5, 7–9, 12, 15].

In 2016, Joye [12] made Cocks' scheme amenable to applications including electronic voting, auction systems, private information retrieval, or cloud computing; Joye proved that Cocks' scheme is homomorphic by considering Cocks' ciphertext as elements of the algebraic group

$$\mathcal{F}_{p,\delta^2} = (\mathbb{F}_p \setminus \{\pm\delta\}) \cup \{\infty\} = \{u \in \mathbb{F}_p \mid u^2 \neq \delta^2\} \cup \{\infty\}$$

for a odd prime p and $\delta \in \mathbb{F}_p^\times$. A similar conclusion can also be reached by considering Cocks' scheme over the polynomial quotient ring $\mathbb{Z}_N[x]/(x^2 - R_{\mathtt{id}})$ for which N is an RSA modulus and $R_{\mathtt{id}}$ is the IBE public key of an identity id [7, 8]. Our two variants are based on the latter structure.

It is well-known that Cocks' scheme is not anonymous due to Galbraith's test [2]. The test has been studied by several researchers [1, 15]. Despite the test, some researchers [1, 9, 12] managed to propose anonymous variants of Cocks' scheme. In this work, we mainly follow the approach of Joye in [12], which does not increase Cocks' ciphertext size or sacrifice its security.

In this work, we use the time-space tradeoff method to propose two variants of Cocks' IBE scheme [10] in the following two aspects:

1. Our first proposal omits the computation of the Jacobi symbol $\left(\frac{a}{b}\right)$ for κ-bit integers a and b, which has $\mathcal{O}(M(\kappa)\log\kappa)$[3] time complexity [6], and the modular multiplicative inverse in Cocks' encryption. In detail, the ciphertext extension is increased by a factor of 2, but the encryption in our proposal only requires several modular multiplications of time complexity $\mathcal{O}(M(\kappa))$. The proposal can also be proved semantic secure under a complexity assumption slightly stronger than the $\mathtt{QR}$ assumption. Moreover, this improvement hardly influences the decryption speed.
2. Inspired by the anonymous IBE scheme without ciphertext expansion proposed in [12, Section 6.2], our second proposal makes the first proposal anonymous under suitable complexity assumptions. Also, this improvement do not influence the ciphertext expansion.

The rest of the paper is organized as follows. In §2, we review the notion of semantic secure and the notion of anonymity. In §3, we describe our first proposal and prove that it is semantic secure. In §4, we describe our second proposal and prove that it is anonymous under suitable assumptions. Concluding remarks are given in §5.

2 Preliminaries

2.1 Identity-based encryption

An *identity-based encryption* (IBE) scheme is defined as a tuple of probabilistic polynomial time ($\mathtt{PPT}$) algorithms ($\mathtt{Setup}, \mathtt{KeyGen}, \mathtt{Enc}, \mathtt{Dec}$):

$\mathtt{Setup}(1^\kappa)$ The setup algorithm $\mathtt{Setup}$ is a randomized algorithm that takes a security parameter 1^κ as input, and outputs a tuple $(\mathtt{mpk}, \mathtt{msk})$, where $\mathtt{mpk}$ denotes the public parameter and $\mathtt{msk}$ denotes the master secret key. The plaintext space is denoted by $\mathtt{M}$.

$\mathtt{KeyGen}(\mathtt{msk}, \mathtt{id})$ The key generation algorithm $\mathtt{KeyGen}$ is a deterministic algorithm that takes $\mathtt{msk}$ and an identity $\mathtt{id}$ as inputs, and outputs a decryption key $\mathtt{sk}_{\mathtt{id}}$ associated with the identity $\mathtt{id}$.

$\mathtt{Enc}(\mathtt{mpk}, \mathtt{id}, m)$ The encryption algorithm $\mathtt{Enc}$ is a randomized algorithm that takes $\mathtt{mpk}$, an identity $\mathtt{id}$ and a plaintext $m \in \mathtt{M}$ as inputs, and outputs a ciphertext c.

$\mathtt{Dec}(\mathtt{mpk}, \mathtt{sk}_{\mathtt{id}}, C)$ The decryption algorithm $\mathtt{Dec}$ is a deterministic algorithm that takes $\mathtt{mpk}$, $\mathtt{sk}_{\mathtt{id}}$ and a ciphertext C as inputs, and outputs the corresponding plaintext m if C is a valid ciphertext, and $\perp$ otherwise.

For any identity $\mathtt{id}$ and all plaintexts $m \in \mathtt{M}$, the *correctness* property requires that

$$\mathtt{Dec}(\mathtt{mpk}, \mathtt{sk}_{\mathtt{id}}, C \leftarrow \mathtt{Enc}(\mathtt{mpk}, \mathtt{id}, m)) = m.$$

2.2 Security notations

Semantic security. The semantic security property states that it is infeasible for any adversary with the limited computation ability to get any information of a plaintext given the corresponding ciphertext. The behaviors of an adversary $\mathcal{A}$ can be simulated by a pair of probabilistic $\mathtt{PPT}$ algorithms $(\mathcal{A}_1, \mathcal{A}_2)$. The game between an adversary and a challenger contains the following four successive phases:

Initialization phase: The challenger runs the algorithm $\mathtt{Setup}$ and keeps the master secret key $\mathtt{msk}$. It then gives the public parameter $\mathtt{mpk}$ to the adversary $\mathcal{A}$.

The first query phase: After receiving $\mathtt{mpk}$, $\mathcal{A}_1$ adaptively chooses an identity subspace $\mathtt{ID}_1 \subseteq \mathtt{ID}$ (The identity space is denoted by $\mathtt{ID}$), and issues the key generation queries and obtains the private key corresponding to each identity in $\mathtt{ID}_1$.

Challenge phase: $\mathcal{A}_1$ chooses a challenge identity $\mathtt{id}^* \notin \mathtt{ID}_1$ and two different plaintexts m_0, $m_1 \in \mathtt{M}$ of the same length. It then outputs them along with some state information $\mathtt{s}$.

[3] $M(\kappa)$ is the time to multiply κ-bit numbers.

GUESS PHASE: The challenger chooses a random bit b and encrypts m_b with $\mathtt{mpk}$ and $\mathtt{id}^*$. It then sends the corresponding ciphertext C to the algorithm $\mathcal{A}_2$. $\mathcal{A}_2$ can issue more key generation queries in the identity space $\mathtt{ID}_2 \subseteq \mathtt{ID}$ which does not contain $\mathtt{id}^*$. The goal of $\mathcal{A}_2$ is to guess the bit b from C and $\mathtt{s}$. It wins the game (carries a successful attack) if the guess is right.

Formally, an IBE scheme is said to be semantically secure if the advantage

$$\mathtt{Adv}_{\mathcal{A}}^{\mathtt{IND\text{-}ID\text{-}CPA}}(\kappa) = \left| \Pr \left[\begin{array}{l} (\mathtt{mpk}, \mathtt{msk}) \xleftarrow{R} \mathtt{Setup}(1^\kappa), \\ (\mathtt{id}^*, m_0, m_1, s) \leftarrow \mathcal{A}_1^{\mathtt{KeyGen}_{\mathtt{msk}}(\cdot)}(\mathtt{mpk}), \ : \ \mathcal{A}_2^{\mathtt{KeyGen}_{\mathtt{msk}}(\cdot)}(s, C) = b \\ b \xleftarrow{R} \{0,1\}, \, C \leftarrow \mathtt{Enc}(\mathtt{mpk}, \mathtt{id}^*, m_b) \end{array} \right] - \frac{1}{2} \right|$$

is negligible. The semantic security can also be called indistinguishable chosen-identity chosen-plaintext security ($\mathtt{IND\text{-}ID\text{-}CPA}$).

Anonymity. The notion of *anonymity* is a strong requirement of privacy: it is infeasible for any adversary with the limited computation ability to get the identity of the recipient from a ciphertext. The behaviors of an adversary $\mathcal{A}$ can also be simulated by a pair of probabilistic $\mathtt{PPT}$ algorithms $(\mathcal{A}_1, \mathcal{A}_2)$. The game between an adversary and a challenger contains the following four successive phases:

INITIALIZATION PHASE: The same as that in §2.2.
THE FIRST QUERY PHASE: The same as that in §2.2.
CHALLENGE PHASE: The adversary chooses two distinct challenge identities $\mathtt{id}_0^*, \mathtt{id}_1^* \notin \mathtt{ID}_1$ and a plaintext $m \in \mathtt{M}$. It then outputs them along with some state information $\mathtt{s}$.
GUESS PHASE: The challenger chooses a random bit b and encrypts m with $\mathtt{mpk}$ and $\mathtt{id}_b^*$. It then sends the corresponding ciphertext C to $\mathcal{A}_2$. $\mathcal{A}_2$ can issue more key generation queries in the identity space $\mathtt{ID}_2 \subseteq \mathtt{ID}$ which does not contain $\mathtt{id}_0^*$ and $\mathtt{id}_1^*$. The goal of $\mathcal{A}_2$ is to guess the bit b from C and $\mathtt{s}$. It wins the game if the guess is right.

Formally, an IBE scheme is said to be *anonymous* if the advantage

$$\mathtt{Adv}_{\mathcal{A}}^{\mathtt{ANO\text{-}ID\text{-}CPA}}(\kappa) = \left| \Pr \left[\begin{array}{l} (\mathtt{mpk}, \mathtt{msk}) \xleftarrow{R} \mathtt{Setup}(1^\kappa), \\ (\mathtt{id}_0^*, \mathtt{id}_1^*, m, \mathtt{s}) \leftarrow \mathcal{A}_1^{\mathtt{KeyGen}_{\mathtt{msk}}(\cdot)}(\mathtt{mpk}), \ : \ \mathcal{A}_2^{\mathtt{KeyGen}_{\mathtt{msk}}(\cdot)}(\mathtt{s}, C) = b \\ b \xleftarrow{R} \{0,1\}, \, C \leftarrow \mathtt{Enc}(\mathtt{mpk}, \mathtt{id}_b^*, m) \end{array} \right] - \frac{1}{2} \right|$$

is negligible in the security parameter κ for any $\mathtt{PPT}$ adversary $\mathcal{A}$.

2.3 Complexity assumption

Let N be a product of two RSA primes p and q. Let $\mathbb{J}_N = \left\{ x \in \mathbb{Z}_N^* \;\middle|\; \left(\frac{x}{N}\right) = 1 \right\}$, i.e., the set of integers whose Jacobi symbols are 1. The set of all quadratic residues is denoted by $\mathbb{QR}_N = \left\{ x \;\middle|\; \exists y \in \mathbb{Z}_N^*, x \equiv y^2 \pmod{N} \right\}$. The following complexity assumption slightly modify the $\mathtt{QR}$ assumption.

Definition 1 (Strong Quadratic Residuosity Assumption). *Given a security parameter κ. A $\mathtt{PPT}$ algorithm $\mathtt{RSAgen}(\kappa)$ generates two RSA primes p and q such that $\frac{p+q}{2}$ is even. Let $N = pq$ and $u \xleftarrow{R} \mathbb{J}_N \setminus \mathbb{QR}_N$. The* Strong Quadratic Residuosity ($\mathtt{SQR}$) Assumption *with respect to $\mathtt{RSAgen}(\kappa)$ asserts that the advantage $\mathtt{Adv}_{\mathcal{A},\mathtt{RSAgen}}^{\mathtt{SQR}}(\kappa)$ defined as*

$$\left| \mathtt{Prob}\left[\mathcal{A}(N, u, x) = 1 \;\middle|\; x \xleftarrow{R} \mathbb{QR}_N \right] - \mathtt{Prob}\left[\mathcal{A}(N, u, x) = 1 \;\middle|\; x \xleftarrow{R} \mathbb{J}_N \setminus \mathbb{QR}_N \right] \right|$$

is negligible for any $\mathtt{PPT}$ adversary $\mathcal{A}$; the probabilities are taken over the experiment of running $(N, p, q) \leftarrow \mathtt{RSAgen}(\kappa)$ and choosing at random $x \in \mathbb{QR}_N$ and $x \in \mathbb{J}_N \setminus \mathbb{QR}_N$.

3 Cocks' IBE scheme with fast encryption

Define the function

$$\mathcal{J}_N(x) = \begin{cases} \perp, & \text{if } \gcd(x, N) \neq 1; \\ i, & \text{if } \gcd(x, N) = 1 \text{ and } \left(\frac{x}{N}\right) = (-1)^i. \end{cases}$$

Cocks' original scheme proceeds in Appendix A. Our first proposal proceeds as follows.

$\texttt{Setup}(1^\kappa)$ Given a security parameter κ, `Setup` generates two RSA primes p and q such that $\frac{p+q}{2}$ is even. Let $N = pq$. `Setup` samples an element $u \xleftarrow{R} \mathbb{J}_N \setminus \mathbb{QR}_N$. The public parameter is $\texttt{mpk} = \{N, u, \texttt{H}\}$ where `H` is a publicly available cryptographic hash function mapping an arbitrary binary string to $\mathbb{J}_N$. The master secret key is $\texttt{msk} = \{p, q\}$.

$\texttt{KeyGen}(\texttt{mpk}, \texttt{msk}, \texttt{id})$ Using `mpk` and `msk`, `KeyGen` sets $R_{\texttt{id}} = \texttt{H}(\texttt{id})$. If $R_{\texttt{id}} \in \mathbb{QR}_N$, `KeyGen` computes $r_{\texttt{id}} = \texttt{H}(\texttt{id})^{1/2} \bmod N$; otherwise it computes $r_{\texttt{id}} = (u\texttt{H}(\texttt{id}))^{1/2} \bmod N$. Finally, `KeyGen` returns $\texttt{sk}_{\texttt{id}} = \{r_{\texttt{id}}\}$ as user's private key.

$\texttt{Enc}(\texttt{mpk}, \texttt{id}, m)$ On inputting `mpk`, an identity `id` and a plaintext $m \in \{0, 1\}$, `Enc` derives the hash value $R_{\texttt{id}} = \texttt{H}(\texttt{id})$. `Enc` then chooses at random two polynomials $f(x), \overline{f}(x)$ of degree 1 from $\mathbb{Z}_N[x]$ and computes

$$g(x) = f(x)^2 \bmod (x^2 - R_{\texttt{id}}) \quad \text{and} \quad \overline{g}(x) = \overline{f}(x)^2 \bmod (x^2 - uR_{\texttt{id}}).$$

The returned ciphertext is $C = \{(-1)^m \cdot g(x), (-1)^m \cdot \overline{g}(x)\}$.

$\texttt{Dec}(\texttt{mpk}, \texttt{sk}_{\texttt{id}}, C)$ On inputting `mpk`, a secret key $\texttt{sk}_{\texttt{id}} = \{r_{\texttt{id}}\}$ and a ciphertext $C = \{c(x), \overline{c}(x)\}$. `Dec` computes

$$m' = \begin{cases} \left(\frac{c(r_{\texttt{id}})}{N}\right) & \text{if } r_{\texttt{id}}^2 \equiv \texttt{H}(\texttt{id}) \pmod N; \\ \left(\frac{\overline{c}(r_{\texttt{id}})}{N}\right) & \text{otherwise.} \end{cases}$$

and recovers the plaintext m as $\mathcal{J}_N(m')$.

Correctness. The correctness of the decryption follows by noticing that when $r_{\texttt{id}}^2 \equiv \texttt{H}(\texttt{id}) \pmod N$ we have

$$m' = \left(\frac{c(r_{\texttt{id}})}{N}\right) = \left(\frac{(-1)^m f(r_{\texttt{id}})^2}{N}\right) = (-1)^m,$$

and thus we can recover the plaintext m by the function $\mathcal{J}_N$. When $r_{\texttt{id}}^2 \equiv u\texttt{H}(\texttt{id}) \pmod N$, we can proceed similarly.

Before proving that the above scheme is semantic secure, we need the following theorem.

Theorem 1. *Let $t \in \mathbb{Z}_N^*$ and R be an element in $\mathbb{J}_N \setminus \mathbb{QR}_N$. If $c(x) = \frac{f(x)^2}{t} \bmod (x^2 - R)$ for some $f(x) \xleftarrow{R} \mathbb{Z}_N[x]$ is a polynomial of degree 1, then the sets*

$$\Omega_k = \left\{ g(x) \in \mathbb{Z}_N[x] \;\middle|\; \deg g(x) = 1, \frac{g(x)^2}{k} \bmod (x^2 - R) = c(x) \right\}$$

are of the same size for each $k \in \mathbb{Z}_N^*$.

Proof. Consider the two sets $\Omega_t, \Omega_{\overline{t}}$, to prove the theorem, it suffices to prove that $\#\Omega_t = \#\Omega_{\overline{t}}$ for fixed t and any $\overline{t} \in \mathbb{Z}_N^*$. Suppose that $\left(\frac{t^{-1}\overline{t}}{p}\right) = (-1)^{i_t}$ and $\left(\frac{t^{-1}\overline{t}}{q}\right) = (-1)^{j_t}$ for $i_t, j_t \in \{0, 1\}$. Since

$$\left(\frac{R^{i_t}}{p}\right) = \left(\frac{t^{-1}\overline{t}}{p}\right) \quad \text{and} \quad \left(\frac{R^{j_t}}{q}\right) = \left(\frac{t^{-1}\overline{t}}{q}\right),$$

there exist $W_p \in \mathbb{Z}_p^*$ and $W_q \in \mathbb{Z}_q^*$ such that

$$W_p^2 R^{i_t} \equiv t^{-1}\overline{t} \pmod p$$
$$W_q^2 R^{j_t} \equiv t^{-1}\overline{t} \pmod q$$

According to the Chinese Remainder Theorem, we have

$$\mathbb{Z}[x]/(N, x^2 - R) \cong \mathbb{Z}[x]/(p, x^2 - R) \oplus \mathbb{Z}[x]/(q, x^2 - R).$$

Therefore, the map $\phi : \Omega_t \to \Omega_{\bar{t}}$ given by $h(x) \mapsto g(x)$ where $\deg g(x) = 1$ and

$$\begin{aligned} g(x) &\equiv W_p x^{i_t} h(x) \pmod{(p, x^2 - R)} \\ g(x) &\equiv W_q x^{j_t} h(x) \pmod{(q, x^2 - R)} \end{aligned}$$

is well defined. In the other direction, the inverse map $\psi : \Omega_{\bar{t}} \to \Omega_t$ is given by $g(x) \mapsto h(x)$ where

$$\begin{aligned} h(x) &\equiv W_p^{-1} \left(R^{-1}x\right)^{i_t} g(x) \pmod{(p, x^2 - R)} \\ h(x) &\equiv W_q^{-1} \left(R^{-1}x\right)^{j_t} g(x) \pmod{(q, x^2 - R)} \end{aligned}$$

It is straightforward to verify that $\psi \circ \phi = 1_{\Omega_t}$ and $\phi \circ \psi = 1_{\Omega_{\bar{t}}}$ where 1_{Ω_t} and $1_{\Omega_{\bar{t}}}$ denote the identity maps on Ω_t and $\Omega_{\bar{t}}$ respectively. □

Theorem 2. *Let $\mathcal{A} = (\mathcal{A}_1, \mathcal{A}_2)$ be an adversary against the* IND-ID-CPA *security of the scheme in §3, making $q_{\mathtt{H}}$ queries to the random oracle* H *that are not followed by extraction queries, and a single query in the* Challenge phase. *Then, there exists an adversary $\mathcal{B}$ against the* SQR *assumption such that*

$$\mathtt{Adv}^{\mathtt{IND\text{-}ID\text{-}CPA}}_{\mathcal{A}}(\kappa) = \frac{q_{\mathtt{H}}}{2} \cdot \mathtt{Adv}^{\mathtt{SQR}}_{\mathcal{B},\mathtt{RSAgen}}(\kappa)$$

The security proof is obtained by following the proof of [12, Appendix A].

Proof. Suppose that $\mathcal{B}$ is given an RSA modulus $N \leftarrow \mathrm{RSAgen}(\kappa)$, a random element $w \in \mathbb{J}_N$ and $u \xleftarrow{R} \mathbb{J}_N \setminus \mathbb{QR}_N$ and is asked to determine whether $w \in \mathbb{J}_N \setminus \mathbb{QR}_N$. $\mathcal{B}$ sets $\mathtt{mpk} = \{N, u, \mathtt{H}\}$ and gives it to $\mathcal{A}_1$, who has oracle access to hash queries and extraction queries, i.e., asking the private key corresponding to each identity in the chosen set $\mathtt{ID}_1$. $\mathcal{B}$ answers the oracle queries as follows:

Hash queries Initially, $\mathcal{B}$ maintains a counter *ctr* initialized to 0 and a list $\mathcal{S}_{\mathtt{H}} \leftarrow \emptyset$ whose entry is in the form $\{\mathtt{id}, R_{\mathtt{id}}, r_{\mathtt{id}}\}$. In addition, $\mathcal{B}$ selects $i^* \xleftarrow{R} \{1, 2, \ldots, q_{\mathtt{H}}\}$.
When $\mathcal{A}$ queries oracle H on an identity id, $\mathcal{B}$ increments *ctr* and checks whether there is an entry whose first component is id. If so, it returns $R_{\mathtt{id}}$; otherwise,

1. If $ctr = i^*$, it returns w and appends $\{\mathtt{id}, w, \perp\}$ to $\mathcal{S}_{\mathtt{H}}$.
2. Otherwise, it returns $h = u^{-j} r^2 \bmod N$ for which $r \xleftarrow{R} \mathbb{Z}_N$ and $j \xleftarrow{R} \{0, 1\}$, and appends $\{\mathtt{id}, h, r\}$ to $\mathcal{S}_{\mathtt{H}}$.

Extraction queries When $\mathcal{A}$ queries the secret key on id, $\mathcal{B}$ first checks whether there is an entry whose first component is id. If not, it invokes H(id) to generate such an entry $\{\mathtt{id}, R_{\mathtt{id}}, r_{\mathtt{id}}\}$. Finally, if $r_{\mathtt{id}} = \perp$, it aborts; otherwise, it returns $r_{\mathtt{id}}$.

Afterwards, $\mathcal{A}_1$ selects a challenge identity $\mathtt{id}^* \notin \mathtt{ID}_1$. If $\mathtt{H}(\mathtt{id}^*) \neq w$, $\mathcal{B}$ returns $b \xleftarrow{R} \{0, 1\}$; otherwise, $\mathcal{B}$ does the following process:

1. Choose at random two polynomials $f(x), \overline{f}(x)$ of degree 1 from $\mathbb{Z}_N[x]$ and $b \xleftarrow{R} \{0, 1\}$. Compute

$$\begin{aligned} g(x) &= f(x)^2 \mod (x^2 - w) \\ \overline{g}(x) &= \overline{f}(x)^2 \mod (x^2 - uw) \end{aligned}$$

The corresponding ciphertext is

$$C_b = \begin{cases} \{g(x), -\overline{g}(x)\}, & \text{if } b = 0; \\ \{-g(x), \overline{g}(x)\}, & \text{otherwise.} \end{cases}$$

2. Give C_b to $\mathcal{A}_2$. $\mathcal{A}_2$ may issue more hash queries and extraction queries on identities except for $\mathtt{id}^*$. Finally, $\mathcal{A}_2$ returns a bit b'.
3. If $b = b'$ return 1; otherwise return 0.

We only need to analyze the success probability of $\mathcal{B}$ solving the SQR assumption in the case of $w = \mathtt{H}(\mathtt{id}^*)$ since the analyse of other cases are the same as those in the proof of [12, Appendix A]. If $w \in \mathbb{QR}_N$, according to the fact that $uw \in \mathbb{J}_N \setminus \mathbb{QR}_N$ and Theorem 1, we conclude that C_b is a valid ciphertext for b. For the same reason, if $w \in \mathbb{J}_N \setminus \mathbb{QR}_N$, we conclude that C_b is a valid ciphertext for $1 - b$. In this case, $\mathcal{B}$ returns 1 if and only if $\mathcal{A}$ loses the game. Let $\epsilon = \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{QR}_N \wedge w = \mathtt{H}(\mathtt{id}^*)\right]$ and $\epsilon' = \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{J}_N \setminus \mathbb{QR}_N \wedge w = \mathtt{H}(\mathtt{id}^*)\right]$. We have

$$\begin{aligned}\mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{QR}_N\right] &= \mathtt{Prob}\left[w = \mathtt{H}(\mathtt{id}^*)\right] \cdot \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{QR}_N \wedge w = \mathtt{H}(\mathtt{id}^*)\right] \\ &\quad + \mathtt{Prob}\left[w \neq \mathtt{H}(\mathtt{id}^*)\right] \cdot \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{QR}_N \wedge w \neq \mathtt{H}(\mathtt{id}^*)\right] \\ &= \frac{\epsilon}{q_{\mathtt{H}}} + \left(1 - \frac{1}{q_{\mathtt{H}}}\right) \cdot \frac{1}{2}\end{aligned}$$

and similarly,

$$\begin{aligned}\mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{J}_N \setminus \mathbb{QR}_N\right] &= \mathtt{Prob}\left[w = \mathtt{H}(\mathtt{id}^*)\right] \cdot \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{J}_N \setminus \mathbb{QR}_N \wedge w = \mathtt{H}(\mathtt{id}^*)\right] \\ &\quad + \mathtt{Prob}\left[w \neq \mathtt{H}(\mathtt{id}^*)\right] \cdot \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{J}_N \setminus \mathbb{QR}_N \wedge w \neq \mathtt{H}(\mathtt{id}^*)\right] \\ &= \frac{1 - \epsilon'}{q_{\mathtt{H}}} + \left(1 - \frac{1}{q_{\mathtt{H}}}\right) \cdot \frac{1}{2}\end{aligned}$$

Consequently,

$$\begin{aligned}\mathtt{Adv}^{\mathtt{SQR}}_{\mathcal{B},\mathtt{RSAgen}}(\kappa) &= \left|\mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{QR}_N\right] - \mathtt{Prob}\left[\mathcal{B}\left(N, u, w\right) = 1 \mid w \in \mathbb{J}_N \setminus \mathbb{QR}_N\right]\right| \\ &= \left|\frac{\epsilon}{q_{\mathtt{H}}} + \left(1 - \frac{1}{q_{\mathtt{H}}}\right) \cdot \frac{1}{2} - \left(\frac{1 - \epsilon'}{q_{\mathtt{H}}} + \left(1 - \frac{1}{q_{\mathtt{H}}}\right) \cdot \frac{1}{2}\right)\right| \\ &= \frac{2}{q_{\mathtt{H}}} \cdot \left|\frac{1}{2} - \left(\frac{1}{2}\epsilon + \frac{1}{2}\epsilon'\right)\right| \\ &= \frac{2}{q_{\mathtt{H}}}\mathtt{Adv}^{\mathtt{IND\text{-}ID\text{-}CPA}}_{\mathcal{A}}(\kappa)\end{aligned}$$

This completes the proof. □

4 Anonymous Cocks' IBE scheme with fast encryption

Galbraith developed a *test* which shows that Cocks' scheme is not anonymous. It was rigorously proved in [1, 15] that the test can distinguish the identity of the recipient from a ciphertext C with overwhelming probability. It is not difficult to see that the scheme in §3 is also not anonymous when we modify *Galbraith's test* as:

$$\mathcal{GT}(R_{\mathtt{id}}, C_i(x)) = \left(\frac{c_{i0}^2 - c_{i1}^2 \alpha_i R_{\mathtt{id}}}{N}\right), \quad i = 1, 2.$$

where $\alpha_1 = 1, \alpha_2 = u$ and $C = (C_1(x), C_2(x)) = (c_{10} + c_{11}x, c_{20} + c_{21}x)$ represents the ciphertext (we still call it Galbraith's test in what follows). To avoid this attack, we should generate two types of ciphertexts whose Galbraith's tests are -1 and $+1$ separately. Obviously, multiplying the ciphertext polynomial by a scalar does not work since the corresponding Galbraith's tests does not change. What about multiplying a polynomial? In fact, a polynomial x is feasible since

$$\mathcal{GT}(R_{\mathtt{id}}, xC_i(x)) = -\mathcal{GT}(R_{\mathtt{id}}, C_i(x)), \quad i = 1, 2.$$

Therefore, inspired by the anonymous IBE scheme without ciphertext expansion from [12, Section 6.2], we can construct the following anonymous IBE scheme with fast encryption and without ciphertext expansion. The scheme proceeds as follows.

$\texttt{Setup}(1^\kappa)$ Given a security parameter κ, $\texttt{Setup}$ generates two RSA primes p and q such that $\frac{p+q}{2}$ is even. Let $N = pq$. $\texttt{Setup}$ samples an element $u \xleftarrow{R} \mathbb{J}_N \setminus \mathbb{QR}_N$. The public parameter is $\texttt{mpk} = \{N, u, \texttt{H}\}$ where $\texttt{H}$ is a publicly available cryptographic hash function mapping an arbitrary binary string to $\mathbb{J}_N$. The master secret key is $\texttt{msk} = \{p, q\}$.

$\texttt{KeyGen}(\texttt{mpk}, \texttt{msk}, \texttt{id})$ Using $\texttt{mpk}$ and $\texttt{msk}$, $\texttt{KeyGen}$ sets $R_{\texttt{id}} = \texttt{H}(\texttt{id})$. If $R_{\texttt{id}} \in \mathbb{QR}_N$, $\texttt{KeyGen}$ computes $r_{\texttt{id}} = \texttt{H}(\texttt{id})^{1/2} \bmod N$; otherwise it computes $r_{\texttt{id}} = (u\texttt{H}(\texttt{id}))^{1/2} \bmod N$. Finally, $\texttt{KeyGen}$ returns $\texttt{sk}_{\texttt{id}} = \{r_{\texttt{id}}\}$ as user's private key.

$\texttt{Enc}(\texttt{mpk}, \texttt{id}, m)$ On inputting $\texttt{mpk}$, an identity $\texttt{id}$ and a plaintext $m \in \{0,1\}$, $\texttt{Enc}$ derives the hash value $R_{\texttt{id}} = \texttt{H}(\texttt{id})$. $\texttt{Enc}$ then chooses at random two polynomials f_1, f_2 of degree 1 from $\mathbb{Z}_N[x]$ and computes (only two of four)

$$\begin{aligned} g_1^0(x) &= (-1)^m f_1(x)^2 && \bmod (x^2 - R_{\texttt{id}}) \\ g_1^1(x) &= (-1)^m x \cdot f_1(x)^2 && \bmod (x^2 - R_{\texttt{id}}) \\ g_2^0(x) &= (-1)^m f_2(x)^2 && \bmod (x^2 - uR_{\texttt{id}}) \\ g_2^1(x) &= (-1)^m x \cdot f_2(x)^2 && \bmod (x^2 - uR_{\texttt{id}}) \end{aligned}$$

$\texttt{Enc}$ also chooses two bits $\beta_1, \beta_2 \xleftarrow{R} \{0,1\}$. The returned ciphertext is

$$C = \left\{ g_1^{\beta_1}(x), g_2^{\beta_2}(x) \right\}.$$

$\texttt{Dec}(\texttt{mpk}, \texttt{sk}_{\texttt{id}}, C)$ On inputting $\texttt{mpk}$, a secret key $\texttt{sk}_{\texttt{id}} = \{r_{\texttt{id}}\}$ and a ciphertext polynomial set $C = \{C_1(x), C_2(x)\}$. If $r_{\texttt{id}}^2 \equiv R_{\texttt{id}} \bmod N$, $\texttt{Dec}$ computes $\sigma = \mathcal{GT}(R_{\texttt{id}}, C_1(x))$; otherwise it computes $\sigma = \mathcal{GT}(R_{\texttt{id}}, C_2(x))$. Finally, $\texttt{Dec}$ computes

$$m' = \begin{cases} \left(\frac{h(r_{\texttt{id}})}{N}\right), & \text{if } \sigma = 1; \\ \left(\frac{r_{\texttt{id}} h(r_{\texttt{id}})}{N}\right), & \text{otherwise.} \end{cases}$$

and recovers the plaintext m as $\mathcal{J}_N(m')$.

Correctness. According to the correctness proof of the scheme in §3, it is enough to show that the decryption is correct when $\sigma = -1$ and $r_{\texttt{id}}^2 \equiv R_{\texttt{id}} \bmod N$. In this case, we have $C_1(x) = g_1^1(x)$ and

$$m' = \left(\frac{r_{\texttt{id}} C_1(r_{\texttt{id}})}{N}\right) = \left(\frac{(-1)^m r_{\texttt{id}}^2 f_1(r_{\texttt{id}})^2}{N}\right) = (-1)^m.$$

Thus, the decryption works correctly.

Remark 1. The amount of computation in the decryption is about twice times larger than that in the scheme from §3. However, the efficiency of the encryption and the size of the ciphertext expansion do not change.

It can be easily seen that the scheme in §4 is also $\texttt{IND-ID-CPA}$ secure by comparing the ciphertexts between the above scheme and the scheme in §3: The ciphertext polynomials for the two schemes differ only by a polynomial x. Therefore, assuming that there exists an $\texttt{IND-ID-CPA}$ adversary $\mathcal{A}$ against the above scheme, we can use $\mathcal{A}$ to break the $\texttt{IND-ID-CPA}$ security of the scheme from §3. The following theorem estimates the size of the first component of the scheme's ciphertext space when $\beta_1 = 0$.

Theorem 3. *With the notations in the above scheme. Fix N, $m \in \{0,1\}$ and assume without loss that $R_{\texttt{id}} = \texttt{H}(\texttt{id}) \in \mathbb{QR}_N$. The set*

$$Z_{N,m,R_{\texttt{id}}} = \left\{ C_{a,b}(x) = (-1)^m (ax+b)^2 \bmod (x^2 - R_{\texttt{id}}) : a, b \xleftarrow{R} \mathbb{Z}_N^* \;\middle|\; ar_{\texttt{id}} \pm b \in \mathbb{Z}_N^* \right\}$$

has size at least $\frac{\varphi(N)(p-3)(q-3)}{16}$ (φ denotes the Euler's totient function). Moreover, the set of the first component of the scheme's ciphertext has size at least $\frac{\varphi(N)(p-3)(q-3)}{8}$ when $\beta_1 = 0$.

Proof. We have

$$C_{a,b}(x) = (-1)^m(ax+b)^2 \equiv (-1)^m \left(a^2 R_{\mathtt{id}} + b^2 + 2abx\right) \pmod{x^2 - R_{\mathtt{id}}}.$$

Suppose that $C_{a_1,b_1}(x) = C_{a_2,b_2}(x)$, we have

$$\begin{aligned} a_1^2 R_{\mathtt{id}} + b_1^2 &\equiv a_2^2 R_{\mathtt{id}} + b_2^2 \pmod{N} \\ 2a_1 b_1 &\equiv 2a_2 b_2 \pmod{N} \end{aligned}$$

This is equivalent to

$$\begin{aligned} (a_1 r_{\mathtt{id}} + b_1)^2 &\equiv (a_2 r_{\mathtt{id}} + b_2)^2 \pmod{N} \\ (a_1 r_{\mathtt{id}} - b_1)^2 &\equiv (a_2 r_{\mathtt{id}} - b_2)^2 \pmod{N} \end{aligned}$$

Fixing a_1 and b_1, if $a_1 r_{\mathtt{id}} + b_1 \in \mathbb{Z}_N^*$ and $a_1 r_{\mathtt{id}} - b_1 \in \mathbb{Z}_N^*$ (this means that $\mathcal{GT}(R_{\mathtt{id}}, C_{a,b}(x)) = 1$), then there are at most 16 choices of $a_2 \in \mathbb{Z}_N^*$ and $b_2 \in \mathbb{Z}_N^*$ for which $C_{a_1,b_1}(x) = C_{a_2,b_2}(x)$. The number of cases of $a_1 r_{\mathtt{id}} \pm b_1 \in \mathbb{Z}_N^*$ for $a_1, b_1 \in \mathbb{Z}_N^*$ is exactly $\varphi(N)(p-3)(q-3)$. This proves the first assertion. It is then clear that $Z_{N,0,R_{\mathtt{id}}} \cap Z_{N,1,R_{\mathtt{id}}} = \emptyset$ since the decryption algorithm can recover the original plaintext. This proves the remaining assertion. □

Given an RSA modulus $N = pq$ and $\triangle \in \mathbb{Z}_N^*$, define the following sets:

- $\mathbb{S}_{N,\triangle} = \left\{u \in \mathbb{Z}_N^* \;\middle|\; \gcd(u^2 - \triangle, N) = 1\right\}$
- $\mathbb{S}_{N,\triangle}^{[-1]} = \left\{u \in \mathbb{Z}_N^* \;\middle|\; \left(\frac{u^2-\triangle}{N}\right) = -1\right\}$
- $\mathbb{S}_{N,\triangle}^{[+1]} = \left\{u \in \mathbb{Z}_N^* \;\middle|\; \left(\frac{u^2-\triangle}{N}\right) = 1\right\}$
- $(\mathbb{S}_{N,\triangle})^2 = \left\{u \in \mathbb{Z}_N^* \;\middle|\; \left(\frac{u^2-\triangle}{p}\right) = \left(\frac{u^2-\triangle}{q}\right) = 1\right\}$

Perron [13] proved that for a prime p and any r relatively prime to p, the set $r + \mathbb{QR}_p$ ($\mathbb{QR}_p$ represents the set of quadratic residues containing 0) contains k *quadratic residues*[4] and k quadratic non-residues when $p = 4k-1$, or $k+1$ quadratic residues and k quadratic non-residues when $p = 4k+1$ and $r \in \mathbb{QR}_p$. Take $r = -\triangle = -R_{\mathtt{id}}$ and assume without loss that $p \equiv 3 \pmod 4$, $q \equiv 1 \pmod 4$ and $R_{\mathtt{id}} \in \mathbb{QR}_N$. There are $\left(\frac{p+1}{4} - 1\right) \times 2 = \frac{p-3}{2}$ elements $u \in \mathbb{Z}_p^*$ for which $\left(\frac{u^2-\triangle}{p}\right) = 1$ and $\left(\frac{q+3}{4} - 2\right) \times 2 = \frac{q-5}{2}$ elements $u \in \mathbb{Z}_q^*$ for which $\left(\frac{u^2-\triangle}{q}\right) = 1$. Thus the size of $(\mathbb{S}_{N,\triangle})^2$ equals $\frac{(p-3)(q-5)}{4}$ and the size of $\mathbb{S}_{N,\triangle}^{[+1]}$ equals $\frac{(p-3)(q-5)}{4} + \frac{(p-3)(q-1)}{4} = \frac{(p-3)(q-3)}{2}$ (See also [15, Corollary 3.4]). Consequently, the set

$$S_{\triangle}^{[+1]} = \left\{a + bx : a, b \xleftarrow{R} \mathbb{Z}_N^* \;\middle|\; \triangle \in \mathbb{QR}_N, \frac{a}{b} \in \mathbb{S}_{N,\triangle}^{[+1]}\right\}$$

has size $\frac{\varphi(N)(p-3)(q-3)}{2}$. It has been proved that the set of the first component of the scheme's ciphertext has size at least $\frac{\varphi(N)(p-3)(q-3)}{8}$ when $\beta_1 = 0$. In order to prove that the scheme achieves anonymity we need to make the following assumption:

Assumption 1 *The set* $\left\{(f,g) \;\middle|\; f \in S_{R_{\mathtt{id}}}^{[+1]},\ g \in S_{uR_{\mathtt{id}}}^{[+1]}\right\}$ *is computationally equivalent to the scheme's ciphertext space when the identity of the recipient is* `id` *and* $\beta_1 = \beta_2 = 0$.

When $\beta_1 = \beta_2 = 1$, it is clear that each component of the ciphertext space has size at least $\frac{\varphi(N)(p-3)(q-3)}{8}$. However, the set

$$S_{\triangle}^{[-1]} = \left\{c + dx : c, d \xleftarrow{R} \mathbb{Z}_N^* \;\middle|\; \triangle \in \mathbb{QR}_N, \frac{c}{d} \in \mathbb{S}_{N,\triangle}^{[-1]}\right\}$$

also has size $\frac{\varphi(N)(p-3)(q-3)}{2}$. Again, we shall make another assumption:

[4] Perron considered the integer 0 as a quadratic residue. We should deal with it carefully.

Assumption 2 *The set* $\left\{(f,g) \;\middle|\; f \in S_{R_{\mathtt{id}}}^{[-1]},\ g \in S_{uR_{\mathtt{id}}}^{[-1]}\right\}$ *is computationally equivalent to the scheme's ciphertext space when the identity of the recipient is* $\mathtt{id}$ *and* $\beta_1 = \beta_2 = 1$.

Theorem 4. *If Assumption 1 and 2 hold, the above scheme is anonymous.*

Proof. Let $\mathtt{id}_0^*$ and $\mathtt{id}_1^*$ be two distinct challenge identities. Without loss of generality, we assume that both $\mathtt{H}(\mathtt{id}_0^*)$ and $\mathtt{H}(\mathtt{id}_1^*)$ are in $\mathbb{QR}_N$. Letting $\triangle = R_{\mathtt{id}_r^*} = \mathtt{H}(\mathtt{id}_r^*)$ for some $r \in \{0,1\}$, consider the following two distributions:

$$D_{0,r} = \left\{ \mathtt{Enc}\left(\mathtt{mpk}, \mathtt{id}_r^*, m\right) = \{g_1^{\beta_1}(x), g_2^{\beta_2}(x)\} \ : \ m \in \{0,1\} \right\}$$
$$D_{1,r} = \left\{ \{a+bx, c+dx\} \ : \ a,b,c,d \xleftarrow{R} \mathbb{Z}_N^*,\ \frac{a}{b} \in \mathbb{S}_{N,\triangle},\ \frac{c}{d} \in \mathbb{S}_{N,\triangle} \right\}$$

We claim that $D_{0,r}$ and $D_{1,r}$ are indistinguishable with overwhelming probability. The first component of an element in $D_{0,r}$ is

$$\begin{cases} a_1 + b_1 x \ : \ \frac{a_1}{b_1} \in \left(\mathbb{S}_{N,\triangle}\right)^2, & \text{if } \beta_1 = 0; \\ a_2 + b_2 x \ : \ \frac{a_2}{b_2} \in \mathbb{S}_{N,\triangle}^{[-1]}, & \text{otherwise.} \end{cases}$$

It follows from Assumption 1 that $S_{\triangle}^{[+1]}$ is computationally equivalent to the first component of the ciphertext when $\beta_1 = 0$, and from Assumption 2 that $S_{\triangle}^{[-1]}$ is computationally equivalent to the first component of the ciphertext when $\beta_1 = 1$. Since $S_{\triangle}^{[+1]} \cup S_{\triangle}^{[-1]} = \left\{a + bx : a, b \in \mathbb{Z}_N^* \;\middle|\; \frac{a}{b} \in \mathbb{S}_{N,\triangle}\right\}$ and β_1 is chosen at random, we deduce that the first component of $D_{0,r}$ and $D_{1,r}$ are computationally equivalent. The similar arguments are valid for the second component, and hence we have proved the claim. Since $D_{1,0}$ and $D_{1,1}$ are also indistinguishable with overwhelming probability, this proves that $D_{0,0}$ and $D_{0,1}$ are indistinguishable with overwhelming probability, and hence the scheme is anonymous. □

5 Conclusion

The encryptions in known variants of Cocks' scheme are much slower than the corresponding decryptions, i.e., the scheme by Clear *et al.* [9] needs about 79 ms and 27 ms for a 128-bit message with a 1024-bit RSA modulus N. Our proposals feature both anonymity and the best encryption time compared with other variants (i.e., nearly 10 times faster than those in the same setting). Furthermore, they inherit the homomorphic property. These make schemes from quadratic residuosity more competitive in the fields of IBE.

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A Cocks' IBE scheme

$\texttt{Setup}(1^\kappa)$ Given a security parameter κ. Generate two RSA primes p and q and let $N = pq$. Sample uniformly an element $u \in \mathbb{J}_N \setminus \mathbb{QR}_N$. Output $\texttt{mpk} = \{N, u, \texttt{H}\}$ and $\texttt{msk} = \{p, q\}$, where $\texttt{H} : \{0,1\}^* \mapsto \mathbb{J}_N$.

$\texttt{KeyGen}(\texttt{msk}, \texttt{id})$ Compute $a = \texttt{H}(\texttt{id})$. If $a \in \mathbb{QR}_N$. Compute $r = a^{1/2} \bmod N$; otherwise, compute $r = (ua)^{1/2} \bmod N$. Output $sk_{\texttt{id}} = \{r\}$.

$\texttt{Enc}(\texttt{mpk}, \texttt{id}, m \in \{\pm 1\})$ Compute $a = \texttt{H}(\texttt{id})$. Choose at random $t, \bar{t} \in \mathbb{Z}_N$ such that $\left(\frac{t}{N}\right) = \left(\frac{\bar{t}}{N}\right) = m$. Compute

$$c = t + \frac{a}{t} \bmod N \quad \textit{and} \quad \bar{c} = \bar{t} + \frac{ua}{\bar{t}} \bmod N$$

Output $C = \{c, \bar{c}\}$.

$\texttt{Dec}(\texttt{mpk}, \texttt{sk}_{\texttt{id}}, C)$ On inputting a secret key $sk_{\texttt{id}} = \{r\}$ and a ciphertext $C = \{c, \bar{c}\}$. Output the plaintext

$$m = \begin{cases} \left(\frac{c+2r}{N}\right), & \text{if } r^2 \equiv a \pmod N; \\ \left(\frac{\bar{c}+2r}{N}\right), & \text{otherwise.} \end{cases}$$

where $a = \texttt{H}(\texttt{id})$.

Remark 2. The above description generalizes the original Cocks' IBE scheme [10] which only considers *Blum integers*, i.e., N is an RSA moduli with $p \equiv q \equiv 3 \pmod 4$. In this case, Cocks' scheme corresponds to the choice $u = -1$ in our description.