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# Efficient Revocable ID-Based Signature With Cloud Revocation Server

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**ABSTRACT** Over the last few years, identity-based cryptosystem (IBC) has attracted widespread attention because it avoids the high overheads associated with public key certificate management. However, an unsolved but critical issue about IBC is how to revoke a misbehaving user. There are some revocable identity-based encryption schemes that have been proposed recently, but little work on the revocation problem of identity-based signature has been undertaken so far. One approach for revocation in identity-based settings is to update users' private keys periodically, which is usually done by the key generation center (KGC). But with this approach, the load on the KGC will increase quickly when the number of users increases. In this paper, we propose an efficient revocable identity-based signature (RIBS) scheme in which the revocation functionality is outsourced to a cloud revocation server (CRS). In our proposed approach, most of the computations needed during key-updates are offloaded to the CRS. We describe the new framework and the security model for the RIBS scheme with CRS and we prove that the proposed scheme is existentially unforgeable against adaptively chosen messages and identity attacks in the random oracle model. Furthermore, we monstate that our scheme outperforms previous IBS schemes in terms of lower computation and communication costs.

**INDEX TERMS** Identity-based signature, revocation, cloud computing, outsourcing.

## I. INTRODUCTION

Digital signature is a critical feature of public key cryptography that provides user identification, authentication and non-repudiation. In traditional public key infrastructure (PKI), users' public keys used to verify signatures are bound with their certificates. Certificate authorities (CAs) are responsible for issuing, maintaining and revoking certificates. In identity-based cryptosystems, however, a user's identity information is the public key. It is a challenge to verify if a user has been revoked or not. In 2001, Boneh and Franklin [1] suggested that the key generator center (KGC) updates secret keys for all non-revoked users periodically. The idea was adopted by many identity-based encryption schemes to realize revocation functionality. Unfortunately, there are two drawbacks with their proposals. First, the KGC must kept online, which brings out some security threats. Second, the overhead at the KGC will dramatically increase as the number of users increases.

With the rapid development of cloud computing, many organizations tend to outsource computation tasks to some

powerful cloud based server. In fact, it is not rare in the history of cryptography to outsource heavy computation tasks to a third party. Quite recently Li *et al.* [2] introduced an approach to outsource the key-updating tasks to a Key Update Cloud Server Provider (KU-CSP) and proposed an efficient revocable identity-based encryption (IBE) scheme. We adopt their approach and apply it to identity-based signature (IBS) settings. A trivial idea is to offload all key-updating tasks to the cloud server. However, there are some security issues we must take into account: the cloud server is not always trusted. So we split the signing key of a user into an initial identity key and a time update key. The former is a long-term key bound to the user's identity and issued by the KGC, and the latter is a short-term key related not only to the user's identity, but also to the current time period. The time update key is issued and updated by a cloud revocation server (CRS) periodically. The CRS cannot forge a signature because it does not hold the complete signing key. To revoke users, the KGC simply notifies the cloud server to stop issuing new time update keys

for them. With this technique, many existing IBS schemes can be improved to be revocable.

### A. RELATED WORK

We discuss a few recently proposed IBS schemes below.

Shamir first introduced the idea of identity-based cryptosystem (IBC) [3], after that Fiat and Shamir [4] presented a construction of IBS scheme based on the factoring problem. Since then, several other proposals based on factoring have been developed [5]–[7].

The first fully practical implementation of identity-based setting emerged in 2001, when Boneh and Franklin [1] proposed an IBE scheme using Weil pairing on elliptic curves. Since then many solutions for IBS schemes with bilinear pairings have been proposed. Sakai *et al.* [8] presented an IBS scheme based on bilinear pairings but no security analysis was given. Choon and Cheon [9] proposed an IBS scheme by utilizing gap bilinear Diffie-Hellman (GDH) groups. Paterson [10] presented another efficient IBS scheme and reduced the security of their scheme to a non-IBS scheme. Hess [11], [12] developed an efficient IBS scheme and extended it to a generic framework, from which several variations can be exported (include ElGamal variations and Schnorr version). The author also considered the key escrow by extending the system to multiple trust authorities. Galindo and Garcia [13] also proposed a Schnorr-like lightweight IBS scheme without pairings. Bellare *et al.* [14] provided a framework for security proof of IBS schemes. Zhang *et al.* [15] proposed an efficient IBS scheme secure under the  $k$ -CAA assumption. Barreto *et al.* [16] presented an identity-based signcryption (IBSC) scheme with bilinear pairings. Based on Water's IBE scheme [17], Paterson and Schuldt [18] presented an efficient IBS scheme and proved its security in the standard model. In recent years, many IBS schemes such as those based on ring signatures, blind signatures, proxy signatures, group signatures etc. were proposed [19]–[22].

There are several efficient proposals of IBS schemes with or without bilinear pairings which have been proposed. However, only a few of them discussed the revocation of misbehaving users. Boneh and Franklin [1] developed a general approach to implement the revocation functionality in identity-based cryptosystems. That is, the KGC generates new secret keys for each non-revoked user periodically, and it simply stops to issue new private keys for the revoked users. Based on this idea, various revocable IBE schemes were proposed [23]–[27] in the past.

The first revocable IBS scheme was proposed by Tsai *et al.* [28], which adopted the revocation technique employed in [27]. The authors proved the security of their scheme in the standard model. Based on their scheme, Hung *et al.* [29] proposed another RIBS scheme with improved security. Sun *et al.* [30] presented an efficient RIBS scheme without pairing but no security proof was given. Recently, Wei *et al.* [31] proposed a forward secure RIBS scheme employing the complete subtree (CS) method where

the KGC must maintain a binary tree on which each node represents a user.

In the above RIBS schemes [28]–[31], the KGC is responsible not only for issuing the initial identity key for each registered user, but also for renewing the time update keys for non-revoked users periodically, which brings two drawbacks. First, the KGC needs to be kept online which is not secure. Second, with the increasing in the number of system users, the computation and communication overheads at the KGC also increase quickly. In this case, the KGC will become the security and performance bottleneck of the whole cryptosystem.

### B. OUR CONTRIBUTIONS

In this work, we propose the first RIBS scheme with a cloud revocation server. We describe the framework of a RIBS scheme with outsourced revocation and formalize the security model. Then we describe our proposed scheme in detail and analyze its security. We prove that our scheme is existentially unforgeable against adaptive chosen message and identity attacks in the random oracle model. Neither a revoked user nor a curious cloud server can forge a valid signature even if they collude with other non-revoked users in the system. We also provide a performance evaluation of our scheme and we compare its performance with other IBS schemes.

### C. ORGANIZATION

The rest of the paper is organized as follows. We present preliminary works in Section II. Section III describes the framework of a RIBS scheme with outsourced cloud revocation server and formalizes its security model. Section IV describes our proposed RIBS scheme in detail. We present the security analysis of our scheme in Section V. Section VI presents the performance evaluation results of our scheme. Section VII concludes the paper.

## II. PRELIMINARY

### A. IDENTITY-BASED SIGNATURE

A typical IBS scheme involves three parties: the KGC, the signer and the verifier. There are four algorithms in an IBS scheme defined as follows.

- **Setup:**  $(MSK, PP) \leftarrow Setup(\lambda)$ . KGC takes as input the security parameter  $\lambda$ , and outputs the master system key  $MSK$  and system public parameters  $PP$  including the system public key  $P_{pub}$ .
- **Initial Key Extraction:**  $S_{ID} \leftarrow KeyExt(MSK, ID)$ . KGC generates a private key for each user. It takes as input  $MSK$  and a user's identity  $ID$ , and returns the private key  $S_{ID}$ .
- **Signing:**  $\sigma \leftarrow Sign(m, S_{ID}, PP)$ . The signer takes as input his/her private key  $S_{ID}$ , the message  $m$  and the public parameters, and outputs a signature  $\sigma$ .
- **Verification:**  $Accept/Reject \leftarrow Ver(\sigma, ID, m, PP)$ . The verifier takes as input the signature  $\sigma$ , the identity  $ID$  of the signer, the message  $m$  and  $PP$ , and returns an "Accept" or a "Reject" to demonstrate if the signature is valid or not.

The consistency of an IBS scheme requires that for any  $S_{ID}$  generated by algorithm  $KeyExt$  when given  $ID$  as input, and for any  $\sigma = Sign(m, S_{ID}, PP)$ ,  $Ver(\sigma, ID, m, PP) = "Accept"$  holds.

**B. BILINEAR PAIRINGS AND COMPUTATIONAL ASSUMPTIONS**

Let  $G$  be an additive cyclic group, whose order is a large prime  $q$ .  $P$  is a generator of  $G$ .  $G_T$  is a multiplicative cyclic group of the same order  $q$ . The map  $\hat{e} : G \times G \rightarrow G_T$  is said to be an admissible bilinear map if it satisfies:

- Bilinearity: For all  $P, Q \in G, x, y \in \mathbb{Z}_q^*$ , there is  $\hat{e}(xP, yQ) = \hat{e}(P, Q)^{xy}$ ;
- Non-degeneracy: There exists  $P, Q \in G$  such that  $\hat{e}(P, Q) \neq 1_{G_T}$ ;
- Computability: For any element  $P, Q \in G$ , there is an polynomial time algorithm to compute  $\hat{e}(P, Q) \in G_T$ .

Next we present the mathematical assumption used in our scheme.

**Computational Diffie-Hellam Problem (CDH):** Given a triple  $(P, aP, bP)$  for some unknown  $a, b \in \mathbb{Z}_q^*$ , we compute  $abP$ .

The CDH assumption says that there is no polynomial time algorithm which can solve the CDH problem with non-negligible probability.

**III. SYSTEM FRAMEWORK AND SECURITY MODEL**

In this section, we describe the system framework of an outsourced RIBS scheme and its security model.

**A. SYSTEM FRAMEWORK**

A RIBS scheme involves three parties: the KGC, the CRS and users (signers and verifiers). At the beginning of the system initialization, the KGC generates and publishes some common parameters and sends a secret master time key to the CRS. Then the KGC issues the initial identity key for each user with its master system key when the user is registered. The CRS issues and updates the users' time update keys according to the revocation user list received from the KGC. If a user is in the revocation user list, then the CRS refuses to update the time update key for the user. We present the framework of our system in Fig. 1. Table 1 shows the notations used in the proposed RIBS scheme.

There are five algorithms in a RIBS scheme: system initialization algorithm ( $Setup$ ), initial key extraction algorithm ( $InitKeyExt$ ), time key updating algorithm ( $TimeKeyUpd$ ), signing algorithm ( $Sign$ ), verification algorithm ( $Ver$ ). The KGC maintains a revocation list (RL) which contains the identities of revoked users and the RL is updated periodically.

- $Setup(1^\lambda)$ : The KGC takes a security parameter  $\lambda$  and outputs a master system key  $msk$ , a master time key  $mtk$ , a time period list  $T = (T_0, T_1, \dots)$  and system public parameters  $PP$ . KGC keeps  $msk$  for itself, and sends  $mtk$  to the CRS securely.  $PP$  is published to all users in the system.

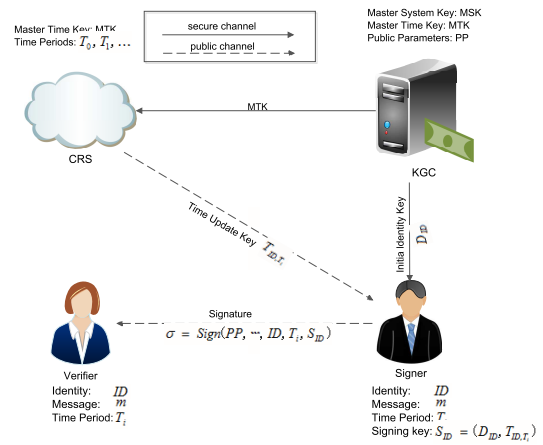


FIGURE 1. Identity-based signature with (cloud) outsourced revocation.

TABLE 1. Summary of notations.

Notation	Description
$ID$	identity of a user $ID \in \{0, 1\}^*$
$T_i$	$i$ th time period
$PP$	system public parameters
$msk$	master system key
$mtk$	master time key
$S_{ID, T_i}$	signing key with identity $ID$ and time period $T_i$
$D_{ID}$	initial identity key with identity $ID$
$T_{ID, T_i}$	time update key with identity $ID$ and time period $T_i$
$H_i$	a map-to-point hash function
$h_i$	an ordinary hash function

- $InitKeyExt(PP, msk, ID)$ : On receiving a register request from the user with identity  $ID$ , the KGC runs this algorithm to issue a secret identity key  $D_{ID}$  with the input  $PP, msk$ , a user's identity  $ID$ , and sends  $D_{ID}$  to the user securely.
- $TimeKeyUpd(PP, mtk, ID, T_i)$ : On receiving an update request from a user, the CRS first checks if the user is in the RL. If it is, the CRS rejects the update request. If not, the CRS runs the algorithm and generates a new time key  $TK_{ID, T_i}$  for the user with the input  $PP, mtk$ , the user's identity  $ID$  and current time period  $T_i$ . A user's signing key  $S_{ID, T_i}$  consists of two parts:  $S_{ID, T_i} = (D_{ID}, TK_{ID, T_i})$ .
- $Sign(PP, m, ID, T_i, S_{ID, T_i})$ : To sign a message  $m$ , the signer runs this algorithm with input  $PP, m$ , his own identity  $ID$ , current time period  $T_i$  and  $S_{ID, T_i}$ , and outputs the signature  $\sigma$ .
- $Ver(PP, m, \sigma, ID, T_i)$ : To verify a signature  $\sigma$  on message  $m$  with the signer's identity  $ID$  and time period  $T_i$ , the verifier runs the algorithm with  $PP, m, \sigma, ID$  and  $T_i$ , and outputs an "Accept" or "Reject" according to the validity of the signature.

The consistency criterion states that for any message  $m$ , any identity  $ID$  and any time period  $T_i$ , if  $\sigma = Sign(PP, m, ID, T_i, S_{ID, T_i})$ , where

$S_{ID, T_i} = (InitKeyExt(msk, ID), TimeKeyUpd(mtk, ID, T_i))$ , then we have  $Ver(PP, m, \sigma, ID, T_i) = "Accept"$  with a high probability.

## B. SECURITY MODEL

Bellare *et al.* [14] first formalized the security of an IBS scheme in 2004, namely, security against existential forgery on adaptively chosen message and identity attacks (EUF-CMA). Based on this formalization, we first consider the following two types of adversaries.

- *Type I adversary  $A_I$* .  $A_I$  is a revoked user. Suppose  $A_I$  has identity  $ID$  and was revoked at time period  $T_i$ .  $A_I$  intends to produce valid signatures after time period  $T_i$ .  $A_I$  still owns the initial identity key  $D_{ID}$ , and we assume that  $A_I$  can collude with other legal users to obtain their identity keys and time update keys at arbitrary time periods.  $A_I$  cannot know its own time update keys after time period  $T_i$ .
- *Type II adversary  $A_{II}$* . Type II adversary can be seen as a curious CRS who tries to create a valid signature in the name of a system user. Since the CRS holds the master time key, so it can obtain the time update key of any user at any time. We also assume that  $A_{II}$  can collude with other users to obtain their identity keys. In this case, the adversary cannot know the target user's identity key  $D_{ID}$ .

We define the security model of an outsourced RIBS scheme through the following two games between a challenger and one of the above two types of adversaries. The game between  $A_I$  and a challenger  $S_I$  is defined below.

*Game 1:*

- **Setup.**  $S_I$  runs the *Setup* algorithm with input security parameter  $\lambda$ , and outputs  $msk$ ,  $mtk$  and  $PP$  as defined in the system framework.  $S_I$  keeps  $msk$ ,  $mtk$  secret and sends  $PP$  to  $A_I$ .
- **Query.**  $A_I$  makes a series of queries to  $S_I$  adaptively, and  $S_I$  responds to each type of queries in the following way.
  - *Initial key extract query ( $ID$ )*.  $A_I$  issues this query to get the initial key of some user with identity  $ID$ .  $S_I$  runs *InitKeyExt* algorithm with input  $(PP, msk, ID)$ , and returns the resulting  $D_{ID}$  to  $A_I$ .
  - *Time key update query ( $ID, T_i$ )*.  $A_I$  issues this query to get the time update key of some user with identity  $ID$  on time period  $T_i$ .  $S_I$  runs the *TimeKeyUpd* algorithm with input  $(PP, mtk, ID, T_i)$ , and returns the resulting  $TK_{ID, T_i}$  to  $A_I$ .
  - *Signing query ( $m, ID, T_i$ )*. When  $A_I$  issues a signing query with a message  $m$ , the identity  $ID$  and time period  $T_i$ ,  $S_I$  runs *Sign* algorithm and outputs a signature  $\sigma$  to  $A_I$ .
- **Forgery.** At last  $A_I$  outputs a tuple  $(m^*, ID^*, T_i^*, \sigma^*)$  with the following two constraints:
  - 1)  $A_I$  does not issue any *time key update query* on  $(ID^*, T_i^*)$ .
  - 2)  $\sigma^*$  is not returned by a *signing query* on input  $(m^*, ID^*, T_i^*)$  issued by  $A_I$ .

It is said that  $A_I$  succeeds in attacking the scheme if  $Ver(PP, m^*, \sigma^*, ID^*, T_i^*) = "Accept"$ .  $A_I$ 's advantage  $Adv_{A_I}(\lambda)$  is defined as

$$Adv_{A_I}(\lambda) = Pr[Ver(PP, m^*, ID^*, T_i^*) = "Accept"].$$

The game between adversary  $A_{II}$  and a challenger  $S_{II}$  is defined as follows.

*Game 2:* The **Setup** and **Query** phases are the same as in *Game 1*.

**Forgery.** At the end of the **Query** phase,  $A_{II}$  outputs a tuple  $(m^*, ID^*, T_i^*, \sigma^*)$  with the following two constraints:

- 1)  $A_{II}$  does not issue any *initial key extract query* on input  $ID^*$ .
- 2)  $\sigma^*$  is not returned by a *signing query* on input  $(m^*, ID^*, T_i^*)$  issued by  $A_{II}$ .

It is said that  $A_{II}$  succeeds in attacking the scheme if  $Ver(PP, m^*, \sigma^*, ID^*, T_i^*) = "Accept"$ .  $A_{II}$ 's advantage  $Adv_{A_{II}}(\lambda)$  is defined as

$$Adv_{A_{II}}(\lambda) = Pr[Ver(PP, m^*, \sigma^*, ID^*, T_i^*) = "Accept"].$$

From the above games we have the following security definition of a RIBS scheme.

*Definition 1 (EUF-RID-CMA):* A RIBS scheme with outsourced revocation is said to be existentially unforgeable against adaptive chosen message and identity attacks if there is no probabilistic polynomial time adversary that has a non-negligible advantage in either Game I or Game II.

## IV. PROPOSED RIBS SCHEME

In this section, we describe our proposed outsourced RIBS scheme. The scheme is composed of the following five algorithms, as defined in Section III-B.

- *Setup*( $\lambda$ ): The KGC runs the algorithm as follows.
  - 1) Choose two cyclic groups  $G$  and  $G_1$  with the same prime order  $q$ . Let  $P$  be a generator of group  $G$ , and  $\hat{e} : G \times G \rightarrow G_1$  be a bilinear map. We compute  $g = \hat{e}(P, P)$ .
  - 2) We randomly choose two secret values  $s, t \in Z_q^*$ , where  $s$  is the master identity key and  $t$  is the master time key. Then, we compute  $P_{pub} = sP, P_t = tP$ . Keep  $s$  secret and transform  $t$  to the CRS in a secure way.
  - 3) We select three hash functions as follows:
 
$$H_1 : \{0, 1\}^* \rightarrow G,$$

$$H_2 : \{0, 1\}^* \times \{0, 1\}^* \rightarrow G,$$

$$h : \{0, 1\}^* \times G \rightarrow Z_q^*.$$
  - 4) We publish the system parameters

$$PP = (q, G, G_1, P, P_{pub}, P_t, H_1, H_2, h).$$

- *InitKeyExt*( $PP, s, ID$ ): For a user with identity  $ID$ , the KGC sets

$$Q_{ID} = H_1(ID), \quad D_{ID} = sQ_{ID},$$



and sends the initial identity key  $D_{ID}$  to the user through a secure channel.

- *TimeKeyUpd*( $PP, t, ID, T_i$ ) : Upon receiving an update request from a user  $ID$  at the time period  $T_i$ , the CRS computes

$$Q_{ID,T_i} = H_2(ID, T_i), \quad T_{ID,T_i} = tQ_{ID,T_i},$$

and sends  $T_{ID,T_i}$  to the user.

- *Sign*( $PP, m, ID, T_i, D_{ID}, T_{ID,T_i}$ ) : Given a message  $m$  and time period  $T_i$ , a signer with identity  $ID$  produces the signature for  $m$  using the identity key  $D_{ID}$  and time update key  $T_{ID,T_i}$  as follows. We randomly choose  $r \in Z_q^*$ , and compute:

$$\begin{aligned} \alpha &= g^r, \\ v &= h(m, \alpha), \\ U &= rP + v(D_{ID} + T_{ID,T_i}). \end{aligned}$$

The signature for the message  $m$  at the time period  $T_i$  is  $\sigma = (U, \alpha)$ .

- *Ver*( $PP, m, \sigma, ID, T_i$ ) : On receiving a signature  $\sigma = (U, \alpha)$  on message  $m$  and time period  $T_i$ , the verifier computes

$$v = h(m, \alpha),$$

and verifies if

$$\hat{e}(U, P) = \alpha \hat{e}(Q_{ID}, P_{pub})^v \hat{e}(Q_{ID,T_i}, P_t)^v.$$

holds. The verifier outputs "Accept" if it does, or "Reject" if not.

We demonstrate the consistency of the scheme as follows:

$$\begin{aligned} \hat{e}(U, P) &= \hat{e}(rP + v(D_{ID} + T_{ID,T_i}), P) \\ &= \hat{e}(rP, P) \hat{e}(D_{ID}, P)^v \hat{e}(T_{ID,T_i}, P)^v \\ &= \hat{e}(P, P)^r \hat{e}(sQ_{ID}, P)^v \hat{e}(tQ_{ID,T_i}, P)^v \\ &= g^r \hat{e}(Q_{ID}, sP)^v \hat{e}(Q_{ID,T_i}, tP)^v \\ &= \alpha \hat{e}(Q_{ID}, P_{pub})^v \hat{e}(Q_{ID,T_i}, P_t)^v. \end{aligned}$$

## V. SECURITY ANALYSIS

In this section, we analyze the security of the proposed scheme in terms of the security model defined in section III-B. We employ the forking lemma technique introduced in [32].

*Lemma 1:* If there is a type I adversary who makes at most  $q_{H_1}, q_{H_2}, q_h, q_e, q_u, q_s$  queries to the hash functions  $H_1, H_2, h$ , initial key extract oracle, time key update oracle and signing oracle respectively and breaks the proposed RIBS scheme with non-negligible probability  $\epsilon_I$ , then there exists a probabilistic challenger who can solve the CDH problem with advantage

$$\epsilon'_I \geq (1 - \frac{1}{q}) \frac{1}{q_{H_2}} \epsilon_I - \frac{q_h}{q}.$$

*Proof:* Suppose  $A_I$  is a type I adversary who wins the attack game with advantage  $\epsilon_I$ . We construct an algorithm  $S_I$  who uses  $A_I$  as a subroutine to solve the CDH problem.

Suppose  $S_I$  is given a CDH instance  $(P, P_a = aP, P_b = bP)$ , where  $P$  is a generator of an additive cyclic group  $G$  of order  $q$ , and  $a, b$  is unknown to  $S_I$ . To compute  $P_{ab} = abP$ ,  $S_I$  simulates a challenger for the adversary as follows.

- **Setup.**  $S_I$  randomly chooses  $s \in Z_q^*$  and sets  $P_{pub} = sP, P_t = P_a$  and sends  $(P, P_{pub}, P_t)$  to the adversary  $A_I$ .  $S_I$  chooses an  $l \in \{1, 2, \dots, q_{H_2}\}$  and maintains three lists  $L_1, L_2$  and  $L_3$  which are initially empty.  $S_I$  answers  $A_I$ 's queries as follows.
- **Query.**

- *Hash query.* We assume that  $A_I$  has already queried the corresponding hash oracles before it makes further queries.  $S_I$  answers three kinds of hash queries as follows.

- \* *H<sub>1</sub>-query.* If  $A_I$  issues a  $H_1$ -query on identity  $ID$ ,  $S_I$  first checks if there is an entry in the list  $L_1$ . If yes,  $S_I$  returns that entry, else  $S_I$  randomly chooses  $x \in Z_q^*$  and returns  $H_1(ID) = xP$  and adds  $(ID, x, H_1(ID))$  into the list  $L_1$ .

- \* *H<sub>2</sub>-query.* Suppose that  $A_I$  issues  $i$ -th  $H_2$ -query on identity  $ID_i$  and time period  $T_j$ ,  $S_I$  first checks if there is an entry in the list  $L_2$ . If so,  $S_I$  returns that entry, else it randomly chooses  $y \in Z_q^*$  and sets

$$H_2(ID_i, T_j) = \begin{cases} yP & i \neq l \\ yP_b & i = l \end{cases}$$

$S_I$  adds  $(ID_i, T_j, y, H_2(ID_i, T_j))$  into list  $L_2$  if  $i \neq l$ , else it adds the entry  $(ID_i, T_j, \perp, H_2(ID_i, T_j))$ , and sets  $ID^* = ID_i$  and  $T^* = T_j$ .

- \* *h-query.* On receiving a  $h$ -query on input  $(m, \alpha)$ ,  $S_I$  first checks if there is an entry in the list  $L_3$ . If there is,  $S_I$  returns the entry, else it returns a randomly chosen  $v \in Z_q^*$ , and adds  $(m, \alpha, h(m, \alpha))$  into list  $L_3$ .

- *Initial key extract query.* On receiving such a query on identity  $ID$ ,  $S_I$  searches list  $L_1$  to find the entry  $(ID, x, H_1(ID))$ , and responds with  $D_{ID} = xP_{pub}$ .

- *Time key update query.* If  $A_I$  issues a query on  $ID_i$  and  $T_j$ ,  $S_I$  first checks if  $(ID_i, T_j) = (ID^*, T^*)$ . If not,  $S_I$  searches the list  $L_2$  to find the entry  $(ID_i, T_j, y, H_2(ID))$ , and responds with  $T_{ID_i,T_j} = yP_t$ , else  $S_I$  sets  $T_{ID_i,T_j} = \perp$ .

- *Signing query.* If  $A_I$  issues a signing query on identity  $ID_i, T_j$  and message  $m$ ,  $S_I$  searches the list  $L_1, L_2$ , to find the corresponding  $H_1(ID)$  and  $H_2(ID, T_i)$ .  $S_I$  then randomly chooses  $U \in G, v \in Z_q^*$  and computes

$$\alpha = \hat{e}(U, P) \hat{e}(P_{pub}, H_1(ID_i))^{-v} \hat{e}(P_t, H_2(ID_i, T_j))^{-v}.$$

$S_I$  searches the list  $L_3$ , if there is an entry  $(m, \alpha, h(m, \alpha))$  and  $h(m, \alpha) \neq v$ , then  $S_I$  aborts, else  $S_I$  returns the signature  $\sigma = (U, \alpha)$  to  $A_I$ . In this case,  $\sigma$  is a valid signature.

- **Forgery.** Finally, the adversary  $A_I$  outputs a signature  $\sigma^* = (U^*, \alpha^*)$  on  $ID', T'$ , and message  $m^*$ .

If  $(ID', T') = (ID^*, T^*)$  and  $Ver(PP, m^*, ID^*, T^*) = "Accept"$ , then output  $\sigma^* = (U^*, \alpha^*)$ . Otherwise, the output "fail" is issued.

Now we apply the forking lemma technique.

$S_I$  runs the above simulated game again with the same random coins, but responds to hash queries issued by  $A_I$  with different random values. By the General Forking Lemma,  $A_I$  will output a different forgery  $\sigma' = (U', \alpha')$  on the same message  $m^*$ , identity  $ID^*$  and time period  $T^*$  with non-negligible probability (the probability would be  $1/9$  for some appropriate chosen parameters. A more in-depth description is given in [32]. Here we assume that  $A_I$  always outputs another valid forgery without loss of generality). Since  $S_I$  runs the game with the same random tape, we have  $\alpha^* = \alpha' = g^r$  from some  $r \in Z_q^*$ , while the underlying hash values corresponding to the two forged signatures are different. We assume that in the signature  $(U^*, \alpha^*)$ ,

$$H_1(ID^*) = x^*P, \quad H_2(ID^*, T^*) = y^*P_b, \quad h(m^*, \alpha^*) = v^*.$$

While in the signature  $(U', \alpha')$ ,

$$H_1(ID^*) = x'P, \quad H_2(ID^*, T^*) = y'P_b, \quad h(m^*, \alpha') = v'.$$

Since the hash values are randomly chosen, so  $x^* \neq x'$ ,  $y^* \neq y'$  and  $v^* \neq v'$  with high probability.

On the other hand, since both  $(U^*, \alpha^*)$  and  $(U', \alpha')$  are valid signatures, we have

$$\hat{e}(U^*, P) = \alpha^* \hat{e}(P_{pub}, x^*P)^{v^*} \hat{e}(P_t, y^*P_b)^{v^*} \quad (1)$$

$$\hat{e}(U', P) = \alpha' \hat{e}(P_{pub}, x'P)^{v'} \hat{e}(P_t, y'P_b)^{v'} \quad (2)$$

By dividing the above two equations, and the condition  $\alpha^* = \alpha'$ , we have

$$\begin{aligned} \hat{e}(U^* - U', P) &= \hat{e}(P_{pub}, P)^{x^*v^* - x'v'} \hat{e}(P_t, P_b)^{y^*v^* - y'v'} \\ &= \hat{e}(sP, P)^{x^*v^* - x'v'} \hat{e}(P_a, P_b)^{y^*v^* - y'v'} \\ &= \hat{e}(P, sP)^{x^*v^* - x'v'} \hat{e}(P, P_{ab})^{y^*v^* - y'v'}, \end{aligned}$$

then

$$\begin{aligned} \hat{e}(P, P_{ab})^{y^*v^* - y'v'} &= \hat{e}(P, U^* - U') \hat{e}(P, sP)^{x'v' - x^*v^*} \\ &= \hat{e}(P, U^* - U') \hat{e}(P, (x'v' - x^*v^*)sP) \\ &= \hat{e}(P, (U^* - U') + (x'v' - x^*v^*)sP) \end{aligned}$$

So

$$\begin{aligned} \hat{e}(P, P_{ab}) &= \hat{e}(P, (U^* - U') + (x'v' - x^*v^*)sP)^{(y^*v^* - y'v')^{-1}} \\ &= \hat{e}(P, (y^*v^* - y'v')^{-1}(U^* - U' \\ &\quad + (x'v' - x^*v^*)sP)) \end{aligned}$$

From the above equation we obtain:

$$P_{ab} = (y^*v^* - y'v')^{-1}(U^* - U' + (x'v' - x^*v^*)sP).$$

So we get the solution of the challenging CDH instance.

Now we analyze the probability that  $S_I$  succeeds. In the *Setup* and *Query* phase, the simulation is perfect except the following two events happen. First,  $S_I$  issues a query  $(ID^*, T^*)$  to  $H_2$  oracle, which has a probability of  $q_{H_2}/q$ .

Second,  $S_I$  returns a signature  $(U, \alpha)$  on  $(m, ID_i, T_j)$  and  $h(m, \alpha)$  has already been in the list  $L_3$  and  $h(m, \alpha) \neq v$ , where  $v$  is randomly chosen by  $S_I$ . This event occurs with a probability of  $q_h/q$ . If the simulation process is executed smoothly, then in the *Forgery* phase,  $A_I$  will output a valid forgery  $(ID', T', m^*, \sigma^*)$  with an advantage of  $\epsilon_I$ . Note that since  $H_2$  is a random oracle, the probability that  $(ID', T', m^*, \sigma^*)$  is valid without any query of  $H_2(ID', T')$  is  $1/q$ . So  $(ID', T')$  has been asked to  $H_2$  oracle in the *Query* Phase with a probability of  $1 - \frac{1}{q}$ . Moreover,  $l$  is randomly chosen from  $\{1, 2, \dots, q_{H_2}\}$ . Thus  $(ID', T') = (ID^*, T^*)$  holds with a probability of  $(1 - \frac{1}{q})\frac{1}{q_{H_2}}$ . So the probability that  $Ver(ID', T', m^*, \sigma^*) = accept$  and  $(ID', T') = (ID^*, T^*)$  is  $(1 - \frac{1}{q})\frac{1}{q_{H_2}}\epsilon_I - \frac{q_h}{q}$ .

From the above analysis we can see that  $S_I$  solves the CDH problem with probability  $(1 - \frac{1}{q})\frac{1}{q_{H_2}}\epsilon_I - \frac{q_h}{q}$ .

**Lemma 2:** If there is a type II adversary who makes at most  $q_{H_1}, q_{H_2}, q_h, q_e, q_u, q_s$  queries to the hash functions  $H_1, H_2, h$ , initial key extract oracle, time key update oracle and signing oracle respectively and breaks the proposed RIBS scheme with a non-negligible probability  $\epsilon_{II}$ , then there exists a probabilistic challenger who can solve the CDH problem with advantage

$$\epsilon'_{II} \geq (1 - \frac{1}{q})\frac{1}{q_{H_1}}\epsilon_{II} - \frac{q_h}{q}.$$

*Proof:* Suppose  $A_{II}$  is a type II adversary who wins the attack game with advantage  $\epsilon_{II}$ . We construct an algorithm  $S_{II}$ , who uses  $A_{II}$  as a subroutine to solve the CDH problem. Suppose  $S_{II}$  is given a CDH instance  $(P, P_a = aP, P_b = bP)$ , where  $P$  is a generator of an additive cyclic group  $G$  of order  $q$ , and  $a, b$  is unknown to  $S_{II}$ . To compute  $P_{ab} = abP$ ,  $S_{II}$  simulates a challenger for the adversary as follows.

- **Setup.**  $S_{II}$  randomly choose  $t \in Z_q^*$ , and sets  $P_{pub} = P_a, P_t = tP$  and sends  $(P, P_{pub}, P_t)$  to the adversary  $A_{II}$ .  $S_{II}$  then randomly chooses  $l \in \{1, 2, \dots, q_{H_1}\}$ .  $S_{II}$  maintains three lists  $L_1, L_2$  and  $L_3$  which are initially empty, and answers  $A_{II}$ 's queries as follows.

- **Query.**

- *Hash query.* We assume that the adversary has already queried the corresponding hash oracles before it makes further queries.

- \*  *$H_1$ -query.* On receiving the  $i$ -th  $H_1$ -query on identity  $ID_i$ ,  $S_{II}$  first checks if there is an entry in the list  $L_1$ . If there is,  $S_{II}$  returns the entry, else  $S_{II}$  randomly chooses  $x \in Z_q^*$  and sets

$$H_1(ID_i) = \begin{cases} xP & i \neq l \\ xP_b & i = l \end{cases}$$

$S_{II}$  returns  $H_1(ID_i)$  to  $A_{II}$  and adds  $(ID_i, x, H_1(ID_i))$  into the list  $L_1$  if  $i \neq l$ , otherwise it adds  $(ID_i, \perp, H_1(ID_i))$  into list  $L_1$  and set  $ID^* = ID_i$ .

- \*  *$H_2$ -query.* On receiving a  $H_2$ -query on  $ID_i$  and  $T_j$ ,  $S_{II}$  first checks if there is an entry in the list  $L_2$ . If yes,  $S_{II}$  returns as the same, else it randomly chooses  $y \in Z_q^*$  and returns

$H_2(ID_i, T_j) = yP$ .  $S_{II}$  then adds  $(ID_i, T_j, y, H_2(ID_i, T_j))$  into list  $L_2$ .

- \* *h-query*. On receiving a *h*-query on input  $(m, \alpha)$ ,  $S_{II}$  first checks if there is an entry in the list  $L_3$ . If yes,  $S_{II}$  returns as the same, otherwise it returns a randomly chosen  $v \in Z_q^*$ , and adds  $(m, \alpha, h(m, \alpha))$  into list  $L_3$ .
- *Initial key extract query*. If  $A_{II}$  issues such a query on identity  $ID$ ,  $S_{II}$  first checks if  $ID = ID^*$ . If not,  $S_{II}$  searches list  $L_1$  to find the entry  $(ID, x, H_1(ID))$ , and responds with  $D_{ID} = xP_{pub}$ , else  $S_{II}$  returns  $\perp$ .
- *Time key update query*. On receiving such a query on  $ID_i$  and  $T_j$ ,  $S_{II}$  searches the list  $L_2$  to find the entry  $(ID_i, T_j, y, H_2(ID_i, T_j))$ , and responds with  $T_{ID_i, T_j} = yP_t$ .
- *Signing query*. If  $A_{II}$  issues a signing query on  $ID, T_i$  and message  $m$ ,  $S_{II}$  first searches the list  $L_1, L_2, L_3$  to find the corresponding  $H_1(ID)$  and  $H_2(ID, T_i)$ .  $S_{II}$  then randomly chooses  $U \in G, v \in Z_q^*$  and computes

$$\alpha = \hat{e}(U, P)\hat{e}(P_{pub}, H_1(ID))^{-v}\hat{e}(P_t, H_2(ID, T_i))^{-v}.$$

$S_{II}$  searches the list  $L_3$ , if there is an entry  $(m, \alpha, h(m, \alpha))$  and  $h(m, \alpha) \neq v$ , then  $S_{II}$  aborts, else  $S_{II}$  returns the signature  $\sigma = (U, \alpha)$  to  $A_{II}$ . In this case,  $\sigma$  is a valid signature.

- **Forgery**. The adversary  $A_{II}$  outputs a forgery  $\sigma^* = (U^*, \alpha^*)$  on identity  $ID'$ , time period  $T'$ , and message  $m^*$ . If  $ID' = ID^*$  and  $Ver(PP, m^*, ID', T') = accept$ ,  $S_{II}$  outputs  $(U^*, \alpha^*)$  as the forgery else it outputs “fail.”

$S_{II}$  runs the simulated game twice with the same random coins, but responds the hash queries with different random values. By the General Forking Lemma,  $A_{II}$  will output a different forgery  $\sigma' = (U', \alpha')$  on the same identity  $ID^*$ , message  $m^*$  and time period  $T_i^*$  with non-negligible probability. We have  $\alpha^* = \alpha' = g^r$ , and assume that in the signature  $(U^*, \alpha^*)$ ,

$$H_1(ID^*) = x^*P_b, \quad H_2(ID^*, T_i^*) = y^*P_t, \quad h(m^*, \alpha^*) = v^*.$$

While in the signature  $(U', \alpha')$ ,

$$H_1(ID^*) = x'P_b, \quad H_2(ID^*, T_i^*) = y'P_t, \quad h(m^*, \alpha^*) = v'.$$

Since the hash values are randomly chosen, so  $x^* \neq x', y^* \neq y'$  and  $v^* \neq v'$  with overwhelming probability.

On the other hand, since both  $(U^*, \alpha^*)$  and  $(U', \alpha')$  are valid signatures, we have

$$\hat{e}(U^*, P) = \alpha^* \hat{e}(P_{pub}, x^*P_b)^{v^*} \hat{e}(P_t, y^*P)^{v^*} \quad (3)$$

$$\hat{e}(U', P) = \alpha' \hat{e}(P_{pub}, x'P_b)^{v'} \hat{e}(P_t, y'P)^{v'} \quad (4)$$

By dividing the above two equations, and the condition  $\alpha^* = \alpha'$ , we have

$$\begin{aligned} \hat{e}(U^* - U', P) &= \hat{e}(P_{pub}, P_b)^{x^*v^* - x'v'} \hat{e}(P_t, P)^{y^*v^* - y'v'} \\ &= \hat{e}(aP, bP)^{x^*v^* - x'v'} \hat{e}(tP, P)^{y^*v^* - y'v'} \\ &= \hat{e}(P, P_{ab})^{x^*v^* - x'v'} \hat{e}(P, tP)^{y^*v^* - y'v'}, \end{aligned}$$

**TABLE 2. Notations of computation costs.**

Notation	Description
$TG_{\hat{e}}$	Time cost of a bilinear pairing map operation.
$TG_m$	Time cost of a scalar multiplication operation.
$TG_a$	Time cost of a point addition operation.
$TG_H$	Time cost of a map-to-point hash function operation.
$T_e$	Time cost of a modular exponentiation operation in $G_T$ .
$T_m$	Time cost of a multiplication operation in $G_T$ .
$T_h$	Time cost of an ordinary hash function operation.

**TABLE 3. Computation time for operations.**

Operation	Time (ms)
$TG_{\hat{e}}$	5.275
$TG_H$	5.101
$TG_m$	1.970
$T_e$	0.331
$T_h$	0.009
$TG_a$	0.003
$T_m$	0.001

then

$$\begin{aligned} \hat{e}(P, P_{ab})^{x^*v^* - x'v'} &= \hat{e}(P, U^* - U') \hat{e}(P, tP)^{y'v' - y^*v^*} \\ &= \hat{e}(P, U^* - U') \hat{e}(P, (y'v' - y^*v^*)tP) \\ &= \hat{e}(P, (U^* - U') + (y'v' - y^*v^*)tP). \end{aligned}$$

So

$$\begin{aligned} \hat{e}(P, P_{ab}) &= \hat{e}(P, (U^* - U') \\ &\quad + (y'v' - y^*v^*)tP)^{(x^*v^* - x'v')^{-1}} \\ &= \hat{e}(P, (x^*v^* - x'v')^{-1}((U^* - U') \\ &\quad + (y'v' - y^*v^*)tP)) \end{aligned}$$

From the above equation we can see that

$$P_{ab} = (x^*v^* - x'v')^{-1}((U^* - U') + (y'v' - y^*v^*)tP).$$

The analysis of  $S_{II}$ 's advantage is just the same as  $S_I$ 's advantage in the simulated Game I. We note that at the end of simulated Game II,  $A_{II}$  will output a valid signature on identity  $ID^*$  with a probability of  $(1 - \frac{1}{q})\frac{1}{qH_1}\epsilon_{II} - \frac{q_h}{q}$ , which is exactly the advantage that  $S_{II}$  succeeds. This concludes the proof.

From Lemma 1 and Lemma 2 we get the following theorem.

**Theorem 1:** The proposed RIBS scheme with outsourced revocation is existence unforgeable against adaptive chosen identity and message attack under the CDH assumption.

## VI. PERFORMANCE EVALUATION

In this section we present the performance evaluation of the proposed scheme, including computation and communication costs. We choose the Ate pairing  $\hat{e} : G \times G \rightarrow G_T$  generated by a point on a super singular elliptic curve

TABLE 4. Comparisons of computation costs.

Schemes	Initial Key Extraction	Time Key Update	Signing	Verifying
Hess's IBS scheme[12]	$TG_m + TG_H$	–	$TG_{\hat{e}} + 2TG_m + T_e$	$2TG_{\hat{e}} + T_e$
cost(ms)	7.071	–	9.546	10.881
Paterson's IBS scheme[10]	$TG_m + TG_H$	–	$3TG_m$	$2TG_{\hat{e}} + 2T_e$
cost(ms)	7.071	–	5.91	11.212
Tsai <i>et al.</i> 's RIBS scheme[28]	$3TG_m$	$3TG_m$	$4TG_m$	$4TG_{\hat{e}}$
cost(ms)	5.91	5.91	7.88	21.1
Hung <i>et al.</i> 's RIBS scheme[29]	$3TG_m$	$3TG_m$	$5TG_m$	$4TG_{\hat{e}} + T_e$
cost(ms)	5.91	5.91	9.85	21.431
Our proposed scheme	$TG_m + TG_H$	$TG_m + TG_H$	$2TG_m$	$TG_{\hat{e}} + 2T_e$
cost(ms)	7.071	7.071	3.94	5.937

over a finite field  $E(F_p)$ , where  $G, G_T$  are groups of prime order  $q$ . To ensure an appropriate security level,  $p$  and  $q$  are large prime numbers with a length of 512 and 160 bits respectively. Table 2 lists the notations used to describe the computation costs of the operations used in the related schemes.

Previous implementations have showed that compared with the computation costs of time-consuming bilinear pairing map, map-to-point hash, scalar multiplication and modular exponentiation operations, the computation costs of point addition, multiplication in  $G_T$  and the ordinary hash operations are trivial. Therefore, we only consider  $TG_{\hat{e}}, TG_H, TG_m, T_e$  when we evaluate the performance.

We evaluate the costs of the above basic operations using MIRACL library [33] on the elastic compute service (ECS) host provided by the Alibaba Cloud platform. The operating system of the host is Ubuntu 14.04 for 64 bit with an Intel(R) Xeon(R) CPU E5-2630 0 @ 2.30GHz, and equipped with 1GB RAM. Table 3 lists the computational time for related operations on the host.

Since there is no other RIBS scheme with CRS based on pairings and proven secure in the random oracle model, we therefore compared the performance of our scheme with some IBS schemes with bilinear pairings but without revocation functionality, and we also compared the performance of our scheme with two RIBS schemes that are secure in the standard model. Table 4 lists the comparisons among the schemes of Hess [12], Paterson [10], Tsai *et al.* [28], Hung *et al.* [29] and ours in terms of computation costs for the initial key extraction, time key update, signing and verification.

There is no revocation in Hess's and Paterson's schemes, but we can extend their schemes to be revocable by using the framework we proposed in section III-A. Tsai and Hung have included revocation functionality in their schemes, but the schemes are designed in the standard model, which means that the hash functions they used are much more inefficient than those used in the random oracle model. In the comparisons, although we omit most of the computation costs of specific, hash operations, the comparison results are still meaningful and referential. We also take into account the

operations which can be precomputed in all the schemes to achieve the best performance from them.

For the computation cost in the initial key extraction, Hess's scheme requires  $TG_m + TG_H$  (7.071ms), same as Paterson's and our scheme. Tsai's and Hung's schemes both require  $3TG_m$  (5.91ms). As for the time key update, our scheme requires  $TG_m + TG_H$  (7.071ms). Tsai's and Hung's schemes require  $3TG_m$  (5.91ms). There is no such operations in Hess's and Paterson's scheme, but if we extend their schemes using the technique we propose, the computation costs of time key update of their schemes will be same as ours, namely,  $TG_m + TG_H$  (7.071). As for the signing process, Hess's scheme requires  $TG_{\hat{e}} + 2TG_m + T_e$  (9.546ms). Paterson's scheme requires  $3TG_m$  (5.91ms). Tsai's scheme requires  $4TG_m$  (7.88ms). Hung's scheme requires  $5TG_m$  (9.85ms) while our scheme only requires  $2TG_m$  (3.94ms). For the verification process, although there are three bilinear maps that need to be evaluated for each signature in our scheme, but some of them can be precomputed. Hess's scheme requires  $2TG_{\hat{e}} + T_e$  (10.881ms). Paterson's scheme requires  $2TG_{\hat{e}} + 2T_e$  (11.212ms). Tsai's scheme requires  $4TG_{\hat{e}}$  (21.1ms). Hung's scheme requires  $4TG_{\hat{e}} + T_e$  (21.431ms). Our scheme requires  $TG_{\hat{e}} + 2T_e$  (5.937ms). Although our scheme seems a little more time consuming than Tsai's and Hung's schemes in the initial key extraction and time key update process, it is worth pointing out that there are several point addition brevity. Moreover, the initial key extraction and time key update process would not be executed frequently, so there is impact on the overall performance. As for the signing and verification process, our scheme outperforms the other schemes.

Table 5 presents the comparisons of communication costs in terms of the size of initial identity key, time update key and signature. Let  $|G|$  denote the size of each element in group  $G$ . If  $G$  is a elliptic curve on finite field  $F_p$ , where  $p$  is a 512 bit prime number, then  $|G|$  denotes the size of a point in  $G$ , which is 1024 bits.  $|q|$  denotes the bit length of  $q$ , which is, for example, 160 bits to achieve an appropriate security level. The initial identity key has a length of  $|G|$  (1024 bits) in schemes of Hess, Paterson and ours, and has a length of  $2|G|$  (2048 bits) in the schemes of Tsai *et al.* and Hung *et al.*



TABLE 5. Comparison of communication costs.

Schemes	Size of Initial Key	Size of Time Key	Size of Signature	Security Model	Revocability
Hess's IBS scheme[12]	$ G $	–	$ G  +  q $	RO	No
length (bits)	1024	–	1184		
Paterson's IBS scheme[10]	$ G $	–	$2 G $	RO	No
length (bits)	1024	–	2048		
Tsai et al.'s RIBS scheme[28]	$2 G $	$2 G $	$4 G $	STD	Yes
length (bits)	2048	2048	4096		
Hung et al.'s RIBS scheme[29]	$2 G $	$2 G $	$4 G $	STD	Yes
length (bits)	2048	2048	4096		
Our proposed scheme	$ G $	$ G $	$ G  +  q $	RO	Yes
length (bits)	1024	1024	1184		

The time update key has the same length as the initial identity key in each scheme except for Hess's and Paterson's schemes. For the size of the signature, Hess's scheme has a length of  $|G| + |q|$  (1184 bits), which is same as ours. Paterson's scheme has a length of  $2|G|$  (2048 bits). Both Tsai's and Hung's schemes has a length of  $4|G|$  (4096 bits). We observe that the communication costs of Hess's scheme and ours are lower than the other schemes. We also present the security model and revocability of the target schemes in table 5.

## VII. CONCLUSION

In this paper, we propose an efficient RIBS scheme with CRS based on bilinear pairings. To eliminate the computation and communication costs of the KGC, revocation functionality is outsourced to a cloud revocation server. We present the framework of the outsourced revocation RIBS scheme and formalize the security model. Our scheme is proven to be secure against existential forgery on adaptively chosen messages and identity attacks in the random oracle model. The performance comparisons show that our scheme has lower computation costs and shorter signature size than previously proposed RIBS schemes thereby demonstrating its suitability for resource-constrained resources such as wireless sensor networks.

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## REFERENCES

- D. Boneh and M. Franklin, "Identity-based encryption from the weil pairing," in *Proc. Annu. Int. Cryptol. Conf.*, 2001, pp. 213–229.
- J. Li, J. Li, X. Chen, C. Jia, and W. Lou, "Identity-based encryption with outsourced revocation in cloud computing," *IEEE Trans. Comput.*, vol. 64, no. 2, pp. 425–437, Feb. 2015.
- A. Shamir, "Identity-based cryptosystems and signature schemes," in *Proc. Workshop Theory Appl. Cryptograph. Techn.*, 1984, pp. 47–53.
- A. Fiat and A. Shamir, "How to prove yourself: Practical solutions to identification and signature problems," in *Proc. Adv. Cryptol.*, 1999, pp. 420–426.
- L. C. Guillou and J. J. Quisquater, *A 'Paradoxical' Identity-Based Signature Scheme Resulting from Zero-Knowledge*, New York, NY USA: Springer, 1990, pp. 216–231.
- T. Okamoto, *Provably Secure and Practical Identification Schemes and Corresponding Signature Schemes*. Berlin, Germany: Springer, 1992.
- H. Tanaka, "A realization scheme for the identity-based cryptosystem," *Electron. Commun. Jpn.*, vol. 73, no. 5, pp. 340–349, 1990.
- R. Sakai, "Cryptosystems based on pairing," in *Proc. Symp. Cryptogr. Inf. Secur. (SCIS)*, Jan. 2001, pp. 26–28.
- J. C. Choon and J. H. Cheon, "An identity-based signature from gap diffie-hellman groups," in *Proc. Int. Workshop Theory Pract. Public Key Cryptogr., Public Key*, 2002, pp. 18–30.
- K. G. Paterson, "ID-based signatures from pairings on elliptic curves," *Electron. Lett.*, vol. 38, no. 18, pp. 1025–1026, Aug. 2002.
- F. Hess, "Exponent group signature schemes and efficient identity based signature schemes based on pairings," 2002.
- F. Hess, *Efficient Identity Based Signature Schemes Based on Pairings*. Berlin, Germany: Springer, 2003.
- D. Galindo and F. D. Garcia, "A schnorr-like lightweight identity-based signature scheme," in *Proc. 2nd Int. Conf. Cryptol. Africa Prog. Cryptol.-AFRICACRYPT*, Gammarth, Tunisia, Jun. 2009, pp. 135–148.
- M. Bellare, C. Namprepmpre, and G. Neven, "Security proofs for identity-based identification and signature schemes," *J. Cryptol.*, vol. 22, no. 1, pp. 1–61, 2009.
- F. Zhang, R. Safavi-Naini, and W. Susilo, "An efficient signature scheme from bilinear parings and its applications," in *Proc. Int. Workshop Theory Pract. Public Key Cryptogr.*, Singapore, Mar. 2004, pp. 277–290.
- P. S. L. M. Barreto, B. Libert, N. McCullagh, and J. J. Quisquater, *Efficient and Provably-Secure Identity-Based Signatures and Signcryption From Bilinear Maps*. Berlin, Germany: Springer, 2005.
- B. Waters, *Efficient Identity-Based Encryption Without Random Oracles*. Berlin, Germany: Springer, 2005.
- K. G. Paterson and J. C. N. Schuldt, *Efficient Identity-Based Signatures Secure in the Standard Model*. Berlin, Germany: Springer, 2006.
- F. Zhang and K. Kim, *Efficient ID-Based Blind Signature and Proxy Signature From Bilinear Pairings*. Berlin, Germany: Springer, 2003.
- X. Chen, F. Zhang, D. M. Konidala, and K. Kim, "A new id-based group signature scheme from bilinear pairings," in *Proc. Int. Workshop Inf. Secur. Appl.*, vol. 3348. 2003, pp. 585–592.
- J. H. Cheon, Y. Kim, and H. J. Yoon, "A new id-based signature with batch verification," in *Proc. Cryptol. Eprint Arch. (IACR)*, 2004, p. 131.
- G. U. Wei-Na, "A new id-based group signature scheme," *Comput. Modernization*, 2010.
- A. Boldyreva, V. Goyal, and V. Kumar, "Identity-based encryption with efficient revocation," in *Proc. ACM Conf. Comput. Commun. Secur. (CCS)*, Alexandria, VA, USA, Oct. 2008, pp. 417–426.
- B. Libert and J.-J. Quisquater, "Efficient revocation and threshold pairing based cryptosystems," in *Proc. 22nd Annu. Symp. Principles Distrib. Comput.*, 2003, pp. 163–171.
- J. H. Seo and K. Emura, "Revocable identity-based encryption revisited: Security model and construction," in *Proc. Public-Key Cryptogr.-PKC*, 2013, pp. 216–234.
- J. H. Seo and K. Emurab, "Revocable hierarchical identity-based encryption," *Theoretical Comput. Sci.*, vol. 542, pp. 44–62, Jul. 2014.
- Y.-M. Tseng and T.-T. Tsai, "Efficient revocable ID-based encryption with a public channel," *Comput. J.*, vol. 55, no. 4, pp. 475–486, 2012.

- [28] T. T. Tsai, Y. M. Tseng, and T. Y. Wu, "Provably secure revocable id-based signature in the standard model," *Secur. Commun. Netw.*, vol. 6, no. 10, pp. 1250–1260, 2013.
- [29] Y. H. Hung, T. T. Tsai, Y. M. Tseng, and S. S. Huang, "Strongly secure revocable id-based signature without random oracles," *Inf. Technol. Control*, vol. 43, no. 3, pp. 264–276, 2014.
- [30] Y. Sun, F. Zhang, L. Shen, and R. Deng, "Revocable identity-based signature without pairing," in *Proc. Int. Conf. Intell. Netw. Collaborat. Syst.*, 2013, pp. 363–365.
- [31] J. Wei, W. Liu, and X. Hu, "Forward-secure identity-based signature with efficient revocation," *Int. J. Comput. Math.*, vol. 93, pp. 1–23, 2016.
- [32] D. Pointcheval and J. Stern, "Security arguments for digital signatures and blind signatures," *J. Cryptol.*, vol. 13, no. 3, pp. 361–396, 2000.
- [33] M. Scott, "Miracl library," (2011). [Online] Available: <http://www.shamus>.



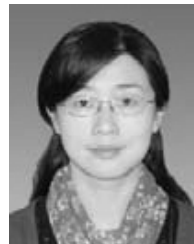
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