Controlled Secret Leakage

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Abstract— Privacy is the claim of individuals, groups and institutions to determine for themselves, when, how and to what extent information about them is communicated to others. How to leak authoritative secrets in an elegant way? The paper aims to solve this problem. The desired security properties i.e. Semantic-Security; Recipient-Designation; Verification-Dependence; Designated-Verifier Signature-Verifiability; Public Signature-Verifiability; Recipient-Ambiguity; Designated-Verifier Recipient-Verifiability; Public Recipient-Verifiability; Signer-Ambiguity; Signer-Verifiability are specified in secret leakage. Based on Chow-Yiu-Hui’s ID-based ring signature scheme and techniques of zero-knowledge proof, an ID-based controlled secret leakage scheme is proposed. The proposed scheme satisfies all specified security properties and can be used in trust negotiation.

Index Terms— privacy, ring signature, authenticated encryption, zero-knowledge proof

I. INTRODUCTION

The rapid growth of the electronic commerce, commonly known as e-commerce or eCommerce, is raising new research questions since the spread of the Internet, a great number of which are centered around security, trust, and privacy. Security, trust, and privacy has objectives including confidentiality (secrecy), data integrity (non-alteration), authentication (identity corroboration of an entity and data origin), and non-repudiation (prevents the denial of previous commitments).

Privacy is important because privacy helps individuals maintain their autonomy and individuality. The most common definition of privacy is the one by Westin: “Privacy is the claim of individuals, groups and institutions to determine for themselves, when, how and to what extent information about them is communicated to others” [1]. According to Westin’s definition, individuals as well as groups and institutions have a right to privacy. In a fully networked society, privacy is seriously endangered and cannot be sufficiently protected by privacy legislation. Cryptography technologies now are valuable tools for privacy protection in addition to privacy legislation.

We consider the following scenario of secret leakage [2]: If a police wants to arrest a criminal but knows few clues about him, so it promises to give an award to a person in some group who could provide the most important clue after the criminal is arrested. A group member Alice can provide something to a designated policeman Bob, but she is not sure whether her message could be the most important one. How to leak this clue in an elegant way? To protect the authoritative secret from propagating and anonymity of the member Alice and the policeman Bob, we propose controlled secret leakage scheme.

It is unsuitable to use traditional authentication on the network where entities are not foreknown to each other. Trust negotiation is now wide used in electronic commerce [3]. In order for strangers to conduct secure transactions, a sufficient level of mutual trust must be established. Trust negotiation is an approach to establishing trust between strangers through the exchange of authoritative secrets. Thus, controlled secret leakage scheme can be used in trust negotiation.

Often when two parties communicate over a network, they have two main security goals: privacy and authentication. Privacy means that a passive adversary who views the ciphertext cannot “understand” the content of the message. Authenticity means that an active adversary cannot successfully fabricate a ciphertext in such a way that Bob will believe that Alice was the originator. Horster et al. first proposed an authenticated encryption scheme [4]. Authenticated encryption scheme aimed to achieve the purpose that the signature can only be verified by some specified recipients while keeping the message secret from the public.

At the conference Asiacrypt 2001, Ron Rivest, Adi Shamir, and Yael Tauman introduced the notion of a ring signature in the paper “How to leak a secret” [5]. A ring signature can be considered as a simplified group signature with no manager, no group setup procedure, and no revocation mechanism against signer’s anonymity. In a ring signature scheme, the information of all possible signers, i.e. ring members, serves as a part of the ring signature for the signed message. Ring signature makes it possible to specify a set of possible signers without revealing which member actually produced the signature. Herein, the anonymous property is referred to as signer-ambiguity. Applications of ring signatures include leaking secrets and authenticated communication. For instance, a ring signature could be used to provide an
prove the fact to anyone else. Beyond the validity of the fact and cannot even later
the fact is false, as long as the verifier follows the protocol.

Identity based public key cryptography proposed by Shamir in 1984 [7] can simplify key management and
remove the necessity of public key certificates. This is desirable, especially for these applications which involve
a large number of public keys in each execution, such as
ring signatures. Recently the bilinear pairings have been
found advantageous in designing various cryptographic
schemes, especially for those using identity-based public
keys, e.g., the identity-based encryption and the identity-
based signature. In [9][10], Boneh and Franklin proposed a fully functional identity-based encryption
scheme. The scheme has chosen ciphertext security in the
random oracle model assuming BDHP is hard. In [11],
Zhang and Kim presented an ID-based ring signature
scheme, which can be built on any GDH group. Their
scheme satisfies the unconditional ambiguity and the non-
forgeability properties. In [8], based on Boneh and
Franklin’s ID-Based encryption scheme [9][10] and
Zhang and Kim’s ID-Based ring signature scheme [11],
Cao et al. construct an ID-based ring authenticated
encryption scheme from bilinear pairings.

In 1985, Goldwasser et al. introduced the notion of
zero-knowledge (ZK) proof [12]. A zero-knowledge
proof is an interactive method for one party (the prover)
to prove to another (the verifier) that a statement is true,
without revealing anything other than the verity of the
statement. An interactive proof usually takes the form of
a challenge-response protocol, in which the prover and
the verifier exchange messages and the verifier outputs
either “accept” or “reject” at the end of the protocol.
Zero-knowledge proofs have the following properties:
Completeness. The verifier always accepts the proof if
the fact is true and both the prover and the verifier follow
the protocol.

Soundness. The verifier always rejects the proof if the
fact is false, as long as the verifier follows the protocol.

Zero-knowledgeness. The verifier learns nothing
beyond the validity of the fact and cannot even later
prove the fact to anyone else.

Demonstrating in zero-knowledge the possession of
digital signatures can protect the privacy of signature
holders from dissemination of signatures by verifiers and
have many cryptographic applications such as
anonymous authentication, identity escrow, publicly
verifiable secret sharing and group signature. Given the
designated-signature, the designated-verifier can verify
that the message was signed by the signer, but is unable
to convince anyone else of this fact.

In this paper, our main contribution is to specify
security properties of secret leakage, define controlled
secret leakage scheme to protect the secret from
propagating and anonymity of the participants, design an
ID-based controlled secret leakage scheme. The rest of
the paper is organized as follows. In the next section, we
give the definition of the controlled secret leakage
scheme and the desired security properties. In Section 3,
we describe the basic concept on bilinear pairings. In
Section 4, we construct our controlled secret leakage
scheme. In Section 4, we show the proposed scheme
satisfies correctness property and security properties. A
conclusion will be given in Section 5.

II. DEFINITIONS

A. Definition of Controlled Secret Leakage Scheme

Definition 1: (Controlled secret leakage scheme).
The controlled secret leakage scheme is specified by
seven algorithms (protocols). The specification of the
controlled secret leakage scheme is shown in Fig. 1.

Signature Generation: The algorithm takes as input
message $M$, the recipient Bob’s public key, the signer
Alice’s private key and all the ring members’ identity list
$L$, which includes the signer Alice, and outputs a ring
signature $S$. The ring signature $S$ will be published in
Bulletin Board System (BBS) or send to the recipient
Bob. We assume that anyone can intercept the signature $S$
in transit.

Message Recovery and Verification: The algorithm
takes as input a signature $S$ and the recipient Bob’s secret
key, outputs the authenticated message $M$ and returns 1 or
0 meaning accept or reject the information that the
signature $S$ is created by a ring member, respectively. We
require that the algorithm outputs the authenticated
message $M$ and returns 1 if the ring signature $S$ is
generated by the signer honestly.

Zero Knowledge Proof of a Ring Signature: Zero-
knowledge proof of a ring signature is a method for the
recipient Bob to prove to a verifier Carol that the
message $M$ is signed by a ring member listed in the ring
set $L$ without revealing any other information. Zero-
knowledge proof can control the secret leakage and
prevent secret propagation. The algorithm takes as input a
signature $S$, a message $M$, the verifier’s private key and a
parameter $A_t$ that can only be computed by the recipient
Bob, and outputs 1 or 0 meaning accept or reject the
information that the signature $S$ is really created by a ring
member, respectively. We require that the algorithm 1
returns 1 if two parties do the protocol honestly.

Zero Knowledge Proof of Recipient: Zero-knowledge
proof of recipient is an interactive method for the
recipient Bob to prove to a verifier Carol that Bob is
actually the designated recipient without revealing any
other information. The algorithm takes as input a signature $S$, a message $M$, the verifier’s private key and a parameter $A_1$ that can only be computed by the recipient $Bob$, and outputs 1 or 0 meaning accept or reject the information that the signature $S$ is really sent to $Bob$, respectively. We require that the algorithm returns 1 if two parties do the protocol honestly.

Publicly Verifiable Proof of a Ring Signature: The algorithm takes as input a signature $S$, a message $M$ and a parameter $A_2$ that can only be computed by the recipient $Bob$, and outputs 1 or 0 meaning accept or reject the information that the signature $S$ is really created by a ring member, respectively. We require that the algorithm returns 1 if $Bob$ does the protocol honestly.

Publicly Verifiable Proof of Recipient: The algorithm takes as input a signature $S$, a message $M$ and a parameter $A_2$ released by $Bob$, and outputs 1 or 0 meaning accept or reject the information that the signature $S$ is really sent to $Bob$, respectively. We require that the algorithm returns 1 if $Bob$ is the real recipient.

Signer Verification: The algorithm takes as input the signature $S$ and a parameter $\beta$ produced when $Alice$ creates the signature, and outputs 1 or 0 meaning accept or reject the information that $Alice$ is the actual signer, respectively. We require that the algorithm returns 1 if $Alice$ is the real signer.

A_2$ released by $Bob$, and outputs 1 or 0 meaning accept or reject the information that the signature $S$ is really sent to $Bob$, respectively. We require that the algorithm returns 1 if $Bob$ is the real recipient.

Figure 1. Controlled secret leakage scheme.

B. Security Properties of Controlled Secret Leakage Scheme

Definition 2: (Security properties of controlled secret leakage scheme). A controlled secret leakage scheme has the following security properties.

Semantic-Security: Any computationally-bounded adversary cannot determine whether his guessed message is the actual message signed by the original signer, although he gets a valid signature.

Recipient-Designation: Only the designated recipient can recover the message and verify the ring signature.

Verification-Dependence: If the actual signer and the legal recipient do not reveal some parameters, any verifier cannot check the validity of the signature even though he gets the message and the corresponding signature.

Designated-Verifier Signature-Verifiability: A designated verifier can be convinced that the message $M$ is signed by a ring member listed in the ring set $L$ by the actual signer or the legal recipient, but the designated verifier is unable to convince anyone else of this fact.

Public Signature-Verifiability: Anyone can verify whether a ring signature is actually produced by at least one of the possible signers after the recipient reveals some parameters.

Recipient-Ambiguity: Anyone cannot know to whom a signature is sent while verifying its validity except the actual signer and the legal recipient.

Designated-Verifier Recipient-Verifiability: A designated verifier can be convinced who is actually the designated recipient by the legal recipient, but the designated verifier is unable to convince anyone else of this fact.
Public Recipient-Verifiability: Anyone can be convinced who is actually the designated recipient by the actual signer or the legal recipient.

Signer-Ambiguity: Anyone cannot determine the identity of the actual signer in a ring of size \( r \) with probability greater than \( 1/r \) if the actual signer is unwilling to expose himself.

Signer-Verifiability: The actual signer can prove to the recipient that it is he who actually signs the signature.

Trust negotiation enables two parties with no pre-existing relationship to establish the trust necessary to perform sensitive transactions via the mutual disclosure of the sensitive content. Therefore, controlled secret leakage scheme can be used in trust negotiation.

III. BILINEAR PAIRINGS

Let \( G_1 \) be a cyclic additive group, whose order is a prime \( q \), and \( G_2 \) be a cyclic multiplicative group with the same order \( q \). Let \( e : G_1 \times G_1 \to G_2 \) be a bilinear pairing with the following properties:

Bilinearity: \( e(aP, bQ) = e(P, Q)^{ab} \) for all \( P, Q \in G_1, a, b \in \mathbb{Z}_q \)

Non-degeneracy: There exists \( P, Q \in G_1 \) such that \( e(P, Q) \neq 1 \), in other words, the map does not send all pairs in \( G_1 \times G_1 \) to the identity in \( G_2 \).

Computability: There is an efficient algorithm to compute \( e(P, Q) \) for all \( P, Q \in G_1 \).

A bilinear map satisfying the three properties above is said to be an admissible bilinear map. We note that the Weil and Tate pairings associated with supersingular elliptic curves or abelian varieties can be modified to create such bilinear maps.

Suppose that \( G_1 \) is an additive group. Now we describe five mathematical problems:

1. Discrete Logarithm Problem (DLP): Given two group elements \( P \) and \( Q \), find an integer \( n \), such that \( Q = nP \) whenever such an integer exists.

2. Decision Diffie-Hellman Problem (DDHP): For \( a, b, c \in \mathbb{Z}_q^* \), given \( P, aP, bP, cP \) decide whether \( c = ab \mod q \). If so, \( P, aP, bP, cP \) is called a valid Diffie-Hellman tuple.

3. Bilinear Diffie-Hellman Problem (BDHP): For \( a, b, c \in \mathbb{Z}_q^* \), given \( P, aP, bP, cP \) compute \( abcP \).

4. Computational Diffie-Hellman Problem (CDHP): For \( a, b \in \mathbb{Z}_q^* \), given \( P, aP, bP \), compute \( abP \).

5. Gap Diffie-Hellman Problem (GDHP): A class of problems where DDHP is easy while CDHP is hard.

When the DDHP is easy but the CDHP is hard on the group \( G_1 \), we call \( G_1 \) a Gap Diffie-Hellman (GDH) group. Such groups can be found on supersingular elliptic curves or hyperelliptic curves over finite field, and the bilinear pairings can be derived from the Weil or Tate pairing \( e : G_1 \times G_1 \to G_2 \).

We have the relationship of the BDHP and CDHP that the BDHP in \( < G_1, G_2, e^e > \) is no harder than the CDHP in \( G_1 \) or \( G_2 \). In other words, an algorithm for CDHP in \( G_1 \) or \( G_2 \) is sufficient for solving BDHP in \( < G_1, G_2, e^e > \).

We assume through this paper that BDHP is intractable, which means there is no polynomial time algorithm to solve BDHP, CDHP or DLP with nonnegligible probability.

IV. ID-BASED CONTROLLED SECRET LEAKAGE SCHEME

Our scheme can be built from any bilinear map \( e : G_1 \times G_1 \to G_2 \) between two groups \( G_1, G_2 \) as long as BDHP in \( G_1 \) is hard and the DDHP in \( G_2 \) is easy.

Setup: Let \( (G_1, +) \) and \( (G_2, \cdot) \) denote cyclic groups of prime order \( q \), let \( P \) be a generator of \( G_1 \) and the bilinear pairing is given as \( e : G_1 \times G_1 \to G_2 \). Pick a random \( s \in \mathbb{Z}_q^* \) and set \( P_{pub} = sP \). Choose cryptographic hash function \( H : \{0, 1\}^n \to Z_q^* \) and \( H_1 : \{0, 1\}^n \to G_1 \), \( H_2 : G_2 \to \{0, 1\}^n \). Choose a pseudorandom generator \( F : \{0, 1\}^n \to G_1 \). The message space is \( M = \{0, 1\}^n \). The master-key is \( s \in \mathbb{Z}_q^* \).

Extract: For a given string \( ID \in \{0, 1\}^n \) the PKG computes \( Q_{ID} = H(ID) \), and sets the private key \( d_{ID} \) to be \( d_{ID} = sQ_{ID} \) where \( s \) is the master key.

Signature Generation: Let \( ID \) be a ring member’s identity, and \( d_{ID} \) be the private key associated with \( ID \) for \( i = 0, 1, \ldots, N-1 \) where \( N \) is the measure of the anonymity set. Let \( L = \{ID_i : 0 \leq i \leq N-1 \} \) be the set of identities. The real signer Alice’s identity \( ID_{Alice} \) is ring member \( ID_A \) listed in \( L \).

Step 1. To sign a message \( M \in \{0, 1\}^n \), the signer, Alice say, who knows the identity \( ID_{Bob} \) of the recipient Bob, whose corresponding secret key is \( d_{ID_{Bob}} \).

Compute \( Q_{ID_{Bob}} = H(ID_{Bob}) \in G_1 \):

1. Choose a random \( \sigma \in \{0, 1\}^n \).
2. Set \( r = H_2(\sigma, M) \).
3. Set the ciphertext of \( M \) to be \( \langle U, V, W \rangle : U = rP, V = \sigma \cdot H_2(g_{ID_{Bob}}^r) \) and \( W = M \cdot H_A(\sigma) \) where \( g_{ID_{Bob}} = e(Q_{ID_{Bob}}, P_{pub}) \in G_2 \).

Step 2. Choose a random \( r_1 \in \mathbb{Z}_q^* \), and compute \( X = r_1P, Y = g_{ID_{Bob}}^r \) and \( Z = H(U \parallel V \parallel W \parallel M \parallel Y) \).

Step 3. To sign \( Z \) Alice utilizes Chow-Yiu-Hui’s ID-based ring signature scheme [13].

1. Choose a random seed \( A \in \{0, 1\}^n \), for \( i = k + 1, \ldots, N - 1, 0, 1, \ldots, k - 1 \) (i.e., the value of \( i \) all modulo \( N \)), compute \( A_i = F(A + i - k) \mod N \), and \( h_i = H(Z, L, A_i) \).
2. Choose a random integer \( r' \in \mathbb{Z}_q^* \), compute \( A_k = r'Q_{ID_{Bob}} - \sum_{i=k}^{r-1} (A_i + h_iQ_{ID_{Bob}}) \).
3. Compute \( h_k = H(Z, L, A_i) \) and \( c = (h_k + r')d_{ID_{Alice}} \).
4. Choose a random \( r_2 \in \mathbb{Z}_q^* \), and compute \( X_i = r_2P, Y_1 = g_{ID_{Bob}}^{r_2} \) and \( c_1 = e(c, H(Y_1)) \).
5. Select 0 (i.e., \( N \)) as the glue value, the resulting ring signature \( S \) is the \((N + 7)\)-tuple \((L, U, V, W, \ldots, Z)\).
Step 4. Finally, Alice sends S to the recipient Bob and keeps the seed A secret. An adversary can intercept S in this step.

Message Recovery and Verification: After receiving the signature $S = (L, U, V, W, X, A_0, ..., A_{N-1}, X_1, c_1)$, the recipient Bob does the following.

Step 1. If $U \not\in G$, reject the signature.

- Compute $\sigma = V \oplus H_d(e(d_{ID_{pub}} \cdot U))$.
- Compute $M = W \oplus H_d(\sigma)$.
- Set $r = H_d(\sigma)$. Test that $U = rP$. If not, reject the signature.

Step 2. Compute $Y = e(d_{ID_{pub}}, X)$ and $Z = H(U \parallel V \parallel W \parallel M \parallel X \parallel Y)$.

Step 3. Compute $Y_1 = e(d_{ID_{pub}}, X_1)$ and $c = c_1 - H_d(Y_1)$.

Step 4. The validity of the signature is verified by checking that $h_i = H(Z, L, A) (0 \leq i \leq N - 1)$ and that

$$e(P, c) = e(P_{pub}, \sum_{i=0}^{N-1} (A_i + h_iQ_{ID})).$$

Zero Knowledge Proof of a Ring Signature: If Bob (or the signer Alice) wants to prove to any designated verifier Carol that the message $M$ is signed by a ring member listed in $L$ without revealing any other information, they can do as follows.

Step 1. Bob computes $W_1 = e(Q_{ID_{pub}}, c)$ and sends the message $M$, the parameter $Y$ and the parameters $(L, U, V, W, X, A_0, ..., A_{N-1}, W_1)$ to Carol.

Step 2. Carol computes $Z = H(U \parallel V \parallel W \parallel M \parallel X \parallel Y)$. Carol can be convinced that the message $M$ is signed by a ring member listed in $L$ if $h_i = H(Z, L, A) (0 \leq i \leq N - 1)$ and $W_1 = e(d_{ID_{pub}}, \sum_{i=0}^{N-1} (A_i + h_iQ_{ID}))$.

Zero Knowledge Proof of Recipient: If Bob wants to prove to any designated verifier Carol that the signature $S$ is actually sent to Bob without revealing any other information, they can do as follows.

Step 1. Bob chooses a random nonce $r_3 \in \{0, 1\}^*$ and computes $W_1 = e(Q_{ID_{pub}}, c)$.

Step 2. Bob sends the message $M$, the nonce $r_3$, the parameter $Y$ and the parameters $(L, U, V, W, X, A_0, ..., A_{N-1}, W_1)$ to Carol.

Step 3. Carol computes $Z = H(U \parallel V \parallel W \parallel M \parallel X \parallel Y)$. Carol can be convinced that the message $M$ is signed by a ring member listed in $L$ if $h_i = H(Z, L, A) (0 \leq i \leq N - 1)$ and $W_1 = e(d_{ID_{pub}}, \sum_{i=0}^{N-1} (A_i + h_iQ_{ID}))$. Otherwise, terminate the protocol.

Step 4. Carol chooses random integers $r_4, r_5, r_6 \in Z_q^*$, and computes $T_1 = r_6 P + r_5 X, U_1 = r_5 Q_{ID_{pub}}, V_1 = (r_6 + H(r_3, T_1, U_1))d_{ID_{pub}}$. Carol sends $(T_1, U_1, V_1)$ to Bob.

Here to sign $(r_3, T_1)$ Carol utilizes Cha-Cheon’s ID-based signature scheme [14].

Step 5. Bob checks the freshness of $r_1$ and the validity of the signature of $(r_3, T_1)$ by checking whether $(P, P_{pub}, U_1 + H(r_3, T_1, U_1)Q_{ID_{pub}}, V_1)$ is a valid Diffie-Hellman tuple.

Step 6. Bob computes $W_2 = H(e(d_{ID_{pub}}, T_1))$ and then sends $W_2$ to Carol.

Step 7. Carol checks whether $W_2 = H(g_1^{r_2} \cdot Y^5)$ where $g_{ID_{pub}} = e(Q_{ID_{pub}}, P_{pub})$. Only if they hold does Carol accept that the signature is sent to Bob.

Publicly Verifiable Proof of a Ring Signature: If Bob (or the signer Alice) wants to prove to any verifier that the message $M$ is signed by a ring member listed in $L$, they can do as follows.

Step 1. Bob publishes the message $M$, the parameter $Y$ and the parameters $(L, U, V, W, X, A_0, ..., A_{N-1}, c)$.

Step 2. The verifier computes $Z = H(U \parallel V \parallel W \parallel M \parallel X \parallel Y)$. The validity of the ring signature is verified by checking that $h_i = H(Z, L, A) (0 \leq i \leq N - 1)$ and that $e(P, c) = e(P_{pub}, \sum_{i=0}^{N-1} (A_i + h_iQ_{ID}))$.

Publicly Verifiable Proof of Recipient: If Bob (or the signer Alice) wants to prove to any verifier that the signature $S$ is actually sent to Bob, they can do as follows.

Step 1. Bob publishes the message $M$, the parameter $Y$, $\sigma$ and the parameters $(L, U, V, W, X, A_0, ..., A_{N-1}, c)$.

Step 2. The verifier computes $Z = H(U \parallel V \parallel W \parallel M \parallel X \parallel Y)$. The validity of the ring signature is verified by checking that $h_i = H(Z, L, A) (0 \leq i \leq N - 1)$ and that $e(P, c) = e(P_{pub}, \sum_{i=0}^{N-1} (A_i + h_iQ_{ID}))$.

Otherwise, terminate the protocol.

Step 3. The verifier does the following.

- Compute $Q_{ID_{pub}} = H_d(ID_{Bob})$.
- Set $r^* = H_d(M)$.
- Compute $U^* = r^* P, V^* = \sigma \oplus H_d(g_{ID_{pub}}^{r^*})$ and $W^* = M \oplus H_d(\sigma)$ where $g_{ID_{pub}} = e(Q_{ID_{pub}}, P_{pub})$.

Step 4. The verifier checks whether $U^* = U, V^* = V$, and $W^* = W$. Only if they hold does the verifier accept that the signature is sent to Bob.

Signer Verification: The actual signer Alice’s identity $ID_{Alice}$ is a ring member listed in $L$. If Alice is willing to prove to the recipient Bob that she actually leaked the message $M$, then she does the following.

Step 1. Bob verifies that the signature $S = (L, U, V, W, X, A_0, ..., A_{N-1}, X_1, c_1)$ is sent to him. The method is same as Message Recovery and Verification.

Step 2. Alice sends the seed $A$ and her identity $ID_{Alice}$ to Bob.

Step 3. For $i = k + 1, ..., N - 1, 0, 1, ..., k - 1$, compute $A_i = F((A + i - k) \mod N)$ and checks if $A_i = A_i$. If they all hold, then Bob convinces that Alice is the real signer. Reject, otherwise.
V. ANALYSIS OF THE PROPOSED SCHEME

A. Correctness

The following theorems are trivially true.

**Theorem 1:** If the \((N + 7)\)-tuple \((L, U, V, W, X, A_0, \ldots, A_{N-1}, X_1, c_1)\) is a signature of a message \(M\) produced by Alice honestly, the recipient Bob will surely recover and verify the message \(M\) correctly from the signature.

**Theorem 2:** If the prover executes Zero Knowledge Proof of a Ring Signature; Zero Knowledge Proof of Recipient; Publicly Verifiable Proof of a Ring Signature; Publicly Verifiable Proof of Recipient; and Signer Verification honestly, an honest verifier can always achieve the stated aim of the protocol.

Number footnotes separately in superscripts 1, 2, \ldots.

Verification-Dependence: If the actual signer and the designated verifier can verify the ring signature.

Semantic-Security: After an adversary gets the message \(M\), the adversary cannot correctly compute the parameter \(Y\) from \(X\) through the equation \(H_v = H(Z, L, A)\) \((0 \leq i \leq N - 1)\) and \(W_i = e(d_{\text{ID}_{\text{Carol}}}, A)\).

Completeness of Zero Knowledge Proof has been show in theorem 2.

Hence we examine soundness of Zero Knowledge Proof of a Ring Signature.

Only the designated verifier Carol, with the private key \(d_{\text{ID}_{\text{Carol}}}, \) can varify that the message \(M\) is signed by a ring member listed in \(L\), through the equation \(h_i = H(Z, L, A)\) \((0 \leq i \leq N - 1)\) and \(W_i = e(d_{\text{ID}_{\text{Carol}}}, X_1)\).

Only the designated recipient Bob or the signer Alice, with the secret parameter \(c\), can prove to the verifier Carol that the message \(M\) is signed by a ring member listed in \(L\). Anyone without the secret parameter \(c\) cannot compute \(e(Q_{\text{ID}_{\text{Carol}}}, c)\). If the adversary tries to compute \(e\) from \((X_1, c_1)\), he has to compute \(Y_1 = e(d_{\text{ID}_{\text{Bob}}}, X_1)\) and it is hard problem without private key \(d_{\text{ID}_{\text{Bob}}}\).

We then show Zero Knowledge Proof of a Ring Signature is also perfect zero-knowledge. Zero-knowledge proof of a ring signature can prevent the secret propagation. For a given message \(M\) and a ring member list \(L\), Carol can construct a simulation of a proof transcript \((L, U, V, W, X, A_0, \ldots, A_{N-1}, W_1, Y)\) as follows:

Step 1. Choose random parameters \((L, U, V, W, X, A_0, \ldots, A_{N-1}, W_1, Y)\).

Step 2. Compute \(Z = H(U || V || W || M || X || Y)\).

Step 3. Compute \(h_i = H(Z, L, A)\) \((0 \leq i \leq N - 1)\) and \(W_i = e(d_{\text{ID}_{\text{Carol}}}, A)\).

Public Signature-Verifiability: If the designated recipient reveals the message \(M\), the parameter \(Y\) and the parameters \((L, U, V, W, X, A_0, \ldots, A_{N-1}, W_1, Y)\), any verifier can check its validity by following the steps in Publicly Verifiable Proof of a Ring Signature. Once a ring member creates a valid signature, the designated recipient can always prove to any verifier that the message \(M\) is signed by a ring member.

Recipient-Ambiguity: If the actual signer and the legal recipient do not reveal the parameter \(\sigma\), any verifier cannot determine who is the real recipient, even though he gets \(M, Y\) and \((L, U, V, W, X, A_0, \ldots, A_{N-1}, W_1, Y)\) in Publicly Verifiable Proof of a Ring Signature. It is difficult for an adversary to drive the parameter \(\sigma\). Since \(H_4\) is one-way hash function, the adversary cannot compute \(\sigma\) from the equation \(W = M \oplus H_4(\sigma)\). If he tries to compute \(\sigma\) from \(U = rP, V = \sigma \oplus H_2(S_{\text{ID}_{\text{Bob}}})\) without known private key \(d_{\text{ID}_{\text{Bob}}}\), he has to compute \(r\) from \(U\) that is a hard DL problem.

Designated-Verifier Signature-Verifiability: Completeness of Zero Knowledge Proof of Recipient has been show in theorem 2.

Here we examine soundness of Zero Knowledge Proof of Recipient.

Only the designated verifier Carol, with the private key \(d_{\text{ID}_{\text{Carol}}},\) can be authenticated by Bob through checking whether \((P, P_{\text{pub}} U_1 + H(T_3, T_1, U_1) Q_{\text{ID}_{\text{Carol}}}, V_1)\) is a valid Diffie-Hellman tuple. Anyone without private key \(d_{\text{ID}_{\text{Carol}}}\) cannot generate the signature of \((r_3, T_3)\). If the adversary tries to impersonate Carol, he has to...
forgery a legitimate signature of (r_i, T_i), that is a hard problem.

Only the authenticated verifier Carol, with the private key d_{Id_{Carol}}, can verify that the message M is signed by a ring member listed in L through the equation h_i = H(Z_i, L, A_i) (0 ≤ i ≤ N − 1) and W_1 = e(d_{Id_{Carol}},
\sum_{i=0}^{N-1} (A_i + h_i Q_{Id_i})). Only the authenticated verifier Carol, with the secret parameter r_A, r_B, can verify that the corresponding ring signature is sent to Bob through the equation W_2 = H(g_{Id_{Bob}}^{r_A} \cdot Y^\alpha) where g_{Id_{Bob}} = e(Q_{Id_{Bob}}, P_{pub}). Anyone without the secret parameter r_A and r_B cannot compute H(g_{Id_{Bob}}^{r_A} \cdot Y^\alpha).

Only the designated recipient Bob, with the secret parameter c and private key d_{Id_{Bob}}, can prove to the verifier Carol that the corresponding ring signature is sent to Bob. Anyone without the secret parameter c and private key d_{Id_{Bob}} cannot compute e(Q_{Id_{Carol}}, c) and H(e(d_{Id_{Bob}}, T_i)).

Zero Knowledge Proof of Recipient is also perfect zero-knowledge. For a given message M and recipient ID_{Bob} listed in a ring member list L, Carol can construct a simulation of a proof transcript (r_3, r_4, r_5, l, U, V, W, X, A_0, ..., A_{n-1}, Y). The following steps in Signer Verification: If a nonsigner l, that is a hard problem.

Step 1. Choose random parameters (r_3, r_4, r_5, l, U, V, W, X, A_0, ..., A_{n-1}, Y).

Step 2. Compute T_i = r_i P + r_2 X, U_i = r_6 Q_{Id_{Carol}}, V_i = (r_6 + H(r_3, T_i, U_i)) d_{Id_{Carol}}.

Step 3. Compute Z = H(U \Vert V \Vert W \Vert M \Vert X \Vert Y).

Step 4. Compute h_i = H(Z_i, L, A_i) (0 ≤ i ≤ N − 1) and W_1 = e(d_{Id_{Carol}}, \sum_{i=0}^{N-1} (A_i + h_i Q_{Id_i})).

Step 5. Compute W_2 = H(g_{Id_{Bob}}^{r_A} \cdot Y^\alpha) where g_{Id_{Bob}} = e(Q_{Id_{Bob}}, P_{pub}).

Public Recipient-Verifiability: If the actual signer or the legal recipient releases the message M, the parameter Y, σ and the parameters (L, U, V, W, X, A_0, ..., A_{n-1}, c), any verifier can check its validity by following the steps in Publicly Verifiable Proof of Recipient. Once a ring member creates a valid signature, the actual signer or the legal recipient can always prove to any verifier that who is actually the designated recipient. If the illegal recipient Eve obtains the message M, the parameter Y and the parameters (L, U, V, W, X, A_0, ..., A_{n-1}, c) in Publicly Verifiable Proof of a Ring Signature and tries to prove that he is the legal recipient, he will seek two parameters σ and r' such that r = H_i(σ, M), U = r' P, V = σ' ⊕ H_2(g_{Id_{Carol}}^{r'}) and W = M ⊕ H_A(σ). But, it is extremely unlikely to have the corresponding parameters.

Signer-Ambiguity: For a given signature, any verifier can only be convinced that the ring signature is actually produced by at least one of the possible signers. If the actual signer does not reveal the seed A_i, then any verifier cannot determine who is the actual signer. The limited anonymity is computational and depends on the security of the pseudorandom generator F.

Signer-Verifiability: According the analysis of Chow-Yiu-Hui [13], the underlying ring signature scheme is non-forgable. Only a ring member can generate a valid signature, the legal recipient can determine the possible signers. If the actual signer ID_{A_i} reveals the seed A_i, which was used to generate all the nonsigners’ parameters A_i (i ≠ k), the recipient can check its validity by following the steps in Signer Verification. If a nonsigner ID_{A_i} (i ≠ k) tries to misuse this technique to prove that he is the signer, he will seek a seed to generate all the parameters A_i (i ≠ l). But, it is extremely unlikely to have a corresponding seed.

VI. CONCLUSION

In this paper, we defined secret leakage scheme which consist of seven procedures to protect the secret from propagating and anonymity of the participants. We also specified ten security properties of secret leakage scheme, i.e. Semantic-Security; Recipient-Designation; Verification-Dependence; Designated-Verifier Signature-Verifiability; Public Signature-Verifiability; Recipient-Ambiguity; Designated-Verifier Recipient-Verifiability; Public Recipient-Verifiability; Signer-Ambiguity; Signer-Verifiability. At last, based on Chow-Yiu-Hui’s ID-based ring signature scheme and techniques of zero-knowledge proof we construct an ID-based controlled secret leakage scheme. We showed that the proposed scheme satisfies all security properties. The proposed scheme can also be used to establish trust in electronic commerce applications.

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