

# Tracing-by-Linking Group Signatures

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**Abstract.** In a group signature [19], any group member can sign on behalf of the group while remaining anonymous, but its identity can be traced in a future dispute investigation. Essentially all state-of-the-art group signatures implement the tracing mechanism by requiring the signer to escrow its identity to an Open Authority (OA) [2, 14, 4, 25, 5, 7, 24]. We call them *Tracing-by-Escrowing (TbE)* group signatures. One drawback is that the OA also has the unnecessary power to trace without proper cause. In this paper we introduce *Tracing-by-Linking (TbL)* group signatures. The signer's anonymity is irrevocable by any authority if the group member signs only once (per event). But if a member signs twice, its identity can be traced by a public algorithm without needing any trapdoor. We initiate the formal study of TbL group signatures by introducing its security model, constructing the first examples, and give several applications. Our core construction technique is the successful transplant of the TbL technique from single-term offline e-cash from the blind signature framework [10, 22, 21] to the group signature framework. Our signatures have size  $O(1)$ .

## 1 Introduction

In a group signature [19], any group member can sign on behalf of the group while remaining anonymous. However, to investigate a dispute, the signer's identity can be *traced*. Essentially all contemporary state-of-the-art group signatures implement the tracing mechanism by requiring the signer to escrow its identity to an Open Authority (OA) [2, 14, 4, 25, 5, 7]. We call them *Tracing-by-Escrowing (TbE)* group signatures. One drawback is that the OA's trapdoor has the unnecessary power to trace any signature without proper cause. For example, a change in government or administration can mandate the OA to trace some past signatures controversially.

In this paper, we initiate the formal study of *Tracing-by-Linking (TbL) group signatures*. In a TbL group signature, the signer's anonymity cannot be revoked by any combination of authorities. However, if a group member signs twice (per event or per *basename*), then its identity can be traced by any member of the public without needing any trapdoor.

Our main **contributions** are

- We initiate the formal study of tracing-by-linking (TbL) group signatures. We introduce its security model, and construct the first several TbL group signatures, and reduce their securities to standard intractability assumptions.
- We extending our constructions from *sign twice and anonymity revoked* to *sign  $k$  times and anonymity revoked*.
- We apply TbL group signatures to several applications, including Direct Anonymous Attestation (DAA), anonymous credentials, offline anonymous e-cash, and e-voting.

The paper is **organized** as follows: Section 2 contains the security model. Section 3 contains preliminaries. Section 4 contains constructions and security theorems. Section 5 contains discussions and applications.

**Related Results:** Essentially all state-of-the-art group signatures are TbE group signatures. The signer anonymity can be revoked by the OA's trapdoor even without cause. Partial key escrows and time-delayed key escrows [36, 30, 3] have been introduced to counteract abuses by the over-powered. The TbL group signature's anonymity is irrevocable by any combination of managers and authorities. There is no OA. In a

ring signature [20, 35, 1] the signer anonymity is also irrevocable. But signing any number of times does not result in anonymity revocation. In a linkable group (resp ring) signature scheme [32, 33, 15, 23, 12], signatures from the same signer can be linked, but its anonymity remains. These *link-but-not-trace* group (resp. ring) signatures typically *tag* the double signer in a way such that future signatures from the same signer can be linked more conveniently.

**Our intuitions:** The core of our construction technique is the successful transplant of the TbL technique from single-term offline e-cash scheme from the blind signature framework [9–11, 21, 22] to the group signature framework. Our TbL group signature has size  $O(1)$ . The essence of our TbL technique is to commit some randomness during group membership certification and then require the signer to use these randomness during a 3-move non-interactive zero-knowledge proof. Double spending implies answering challenges twice with the same *certified commitments* and it results in the extraction of the double signer’s secret identity.

## 2 Security Model

We present a security model for the tracing-by-linking (TbL) group signature. In a nutshell, we replace the triplet of security notions, *anonymity*, *full traceability* and *non-frameability*, of TbE group signatures [4, 5] by a new triplet for TbL group signatures: *irrevocable anonymity*, *full linkability* and *non-slanderability*. Motivated by the DAA (Direct Anonymous Attestation) [12] application, our system consists of three types of entities in multitudes:

- Managers of Groups, or, equivalently, Certificate Authorities (CA’s), with serial number *cnt* which stands for *counter value*.
- Users, or, equivalently, TPM (Trusted Platform Module), whose serial number is *id*.
- Verifiers with serial number *bsn* which stands for *basename*.

Having multiple CA’s is equivalent to having multiple groups, and thus our model extends the single-group models of [4, 25, 5]. Having multiple verifiers allows multiple signatures, one set per verifier serial number *bsn*, and thus increases its usefulness of TbL group signatures.

**Syntax.** A TbL group signature is a tuple (Init, GKg, UKg, Join, lss, GSig, GVf, Link, Indict) where:

- **Init:**  $1^\lambda \rightarrow \text{param}$ . On input the security parameter  $1^\lambda$ , Protocol Init generates public system parameters *param*. Included: an efficiently samplable one-way NP-relation whose specification is  $\langle \mathcal{R}_{user} \rangle$ , an efficiently samplable family of trapdoor one-way NP-relations whose specifications constitute  $\mathcal{F} = \{ \langle \mathcal{R}_{CA,i} \rangle : i \}$  and whose trapdoors are denoted  $gsk_i$ ’s, and an initially-empty list of generated users denoted *UL*, and an initially-empty list of generated groups denoted *GL*.
- **GKg:**  $\text{cnt} \xrightarrow{\$} \langle \mathcal{R}_{CA,\text{cnt}} \rangle$ . On input *cnt*, Protocol GKg samples  $\mathcal{F}$  to get a relation whose specification is  $\langle \mathcal{R}_{CA,\text{cnt}} \rangle$  and whose trapdoor is  $gsk_{\text{cnt}}$ , and adds an entry  $(\text{cnt}, \langle \mathcal{R}_{CA,\text{cnt}} \rangle)$  to the group list *GL*. By convention,  $\langle \mathcal{R}_{CA,\text{cnt}} \rangle$  includes  $gpk_{\text{cnt}}$ .
- **UKg:**  $\text{id} \xrightarrow{\$} (usk_{\text{id}}, upk_{\text{id}}) \in \mathcal{R}_{user}$ . Protocol UKg accepts input *id* to sample a key pair from  $\mathcal{R}_{user}$ , adds an entry  $(\text{id}, upk_{\text{id}})$  to the user list *UL*.
- **Join, lss** is a pair of interactive protocols with common inputs  $\text{cnt} \in GL$  and  $\text{id} \in UL$ , and *lss*’s additional input  $gsk_{\text{cnt}}$ , and *Join*’s additional inputs  $usk_{\text{id}}$ . At the conclusion, *join* obtains extended secret key  $xsk_{\text{id},\text{cnt}}$ , extended public key  $xpk_{\text{id},\text{cnt}}$  which includes a certificate  $cert_{\text{id},\text{cnt}}$  satisfying  $(xpk_{\text{id},\text{cnt}}, cert_{\text{id},\text{cnt}}) \in \mathcal{R}_{CA,\text{cnt}}$  and  $(xsk_{\text{id},\text{cnt}}, xpk_{\text{id},\text{cnt}}) \in \mathcal{R}_{user}$ , such that *lss* does not know  $xsk_{\text{id},\text{cnt}}$ , and an entry  $(\text{id}, \text{cnt}, xpk_{\text{id},\text{cnt}})$  is added to the public system parameters *param*. Below, we may sometimes use the notations *xpk* (resp. *xsk*) and *upk* (resp. *usk*) interchangeably without ambiguity from context.
- **GSig:**  $(\text{id}, \text{cnt}, xsk_{\text{id},\text{cnt}}, \text{bsn}, M) \rightarrow \sigma$ . It takes inputs  $\text{id} \in UL$ ,  $\text{cnt} \in GL$ ,  $xsk_{\text{id},\text{cnt}}$ , *bsn*, and a message *M*, returns a signature  $\sigma$ . By convention, the *extended signature*  $\sigma$  includes *cnt*, *bsn*, and *M*. Optionally, an additional input  $\mu_{\text{id},\text{cnt},\text{bsn}}$  can be included to bookkeep the number of times signatures have been generated for each triple  $(\text{id}, \text{cnt}, \text{bsn})$ .
- **GVf:**  $(\sigma, \text{cnt}, \text{bsn}) \rightarrow 0 \text{ or } 1$ . It takes input a signature  $\sigma$ , returns either 1 or 0 for valid or invalid. If  $\sigma$  is an extended signature, then it includes *cnt* and *bsn*.

- **Link**:  $(\sigma_1, \dots, \sigma_{k+1}) \rightarrow 0$  or 1. It takes inputs  $k + 1$  valid signatures,  $\sigma_i$ ,  $1 \leq i \leq k + 1$ , returns either 1 or 0 for linked or unlinked.
- **Indict**:  $(\sigma_1, \dots, \sigma_{k+1}) \rightarrow \text{id}$ . It takes  $k + 1$  valid and linked signatures  $\sigma_i$ ,  $1 \leq i \leq k + 1$ , returns **id**.

**Definition 1 (Correctness).** For integer  $i$ ,  $1 \leq i \leq k + 1$ , let  $\sigma_i = \text{GSig}(id_i, cnt_i, xsk_{id_i, cnt_i}, bsn_i, M_i)$ . A TbL group signature has verification correctness if  $\text{GVf}(\sigma_1) = 1$  with probability one (or, equivalently,  $\text{GVf}(\sigma_i) = 1$  with probability one for each  $i$ ,  $1 \leq i \leq k + 1$ ). It has linking correctness if  $\text{Link}(\sigma_1, \dots, \sigma_{k+1}) = 0$  with overwhelming probability when the  $k + 1$  triples  $(id_i, cnt_i, bsn_i)$ ,  $1 \leq i \leq k + 1$ , are not all identical. It has indictment correctness if  $\text{Link}(\sigma_1, \dots, \sigma_{k+1}) = 1$  and  $\text{Indict}(\sigma_1, \dots, \sigma_{k+1}) = id_1$  with overwhelming probability when the  $k + 1$  triples  $(id_i, cnt_i, bsn_i)$ ,  $1 \leq i \leq k + 1$ , are all identical. It is correct if it has verification correctness, linking correctness, and indictment correctness.

The following **oracles** are the attacker’s tools.

- The *Random Oracle*  $\mathcal{H}$ : We use the Random Oracle normally.
- The *Corruption Oracle*  $\mathcal{CO} : (\text{id}, \text{cnt}) \rightarrow xsk_{\text{id}, \text{cnt}}$ . Upon input the  $\text{id} \in UL$ , it outputs  $xsk_{\text{id}}$ .
- The *k-Signing Oracle*  $\mathcal{SO}_k : (\text{id}, \text{cnt}, \text{bsn}, M) \rightarrow \sigma$ . Upon inputs a user  $\text{id} \in UL$ , a CA  $\text{cnt} \in GL$ , a verifier  $\text{bsn}$ , and a message  $M$ , it outputs a signature. For each tuple  $(\text{id}, \text{cnt}, \text{bsn})$ , at most  $k$  query with the same triple  $(\text{id}, \text{cnt}, \text{bsn})$  are allowed regardless of the message  $M$ . This restriction reflects the reality that honest group members do not over-sign in TbL group signatures. We adopt the convention that  $\mathcal{SO}_k$  will output *NULL* upon query inputs that repeat a triple  $(\text{id}, \text{cnt}, \text{bsn})$  more than  $k$  times.
- The *Group Corruption Oracle*:  $\mathcal{GCO}(\text{cnt})$  accepts input  $\text{cnt} \in GL$ , and outputs the group trapdoor  $gsk_{\text{cnt}}$ . The group manager  $\text{cnt}$  continues to function honestly, but the attacker can observe its communications.
- The *Add User Oracle*:  $\mathcal{AUO}(\text{id})$  adds a user with identity  $\text{id}$  and sampled sk-pk pair  $\text{UKg}(\text{id}) \xrightarrow{\$} (usk_{\text{id}}, upk_{\text{id}})$  to  $UL$ .
- The *Join Oracle*:  $\mathcal{JO}(\text{id}, usk_{\text{id}}, upk_{\text{id}})$  allows the attacker to interact, in the role of the Join Protocol, with the *lss* Protocol.
- The *Issue Oracle*:  $\mathcal{IO}(\text{cnt}, gsk_{\text{cnt}}, gpk_{\text{cnt}})$  allows the attacker to interact with the Join Protocol, in the role of the *lss* Protocol after the attacker corrupts with  $\mathcal{GCO}(\text{cnt})$ .

We adopt the *static attacker model* where the attacker corrupts users at the beginning of the security experiments only, and the Simulator knows which users are corrupted. Issues with *adaptive attackers* [17], *reset attackers* [18], or UC (Universal Composability) attackers [16] are left to future research.

**Irrevocable k-Anonymity.** Irrevocable anonymity for TbL group signature is defined in the following experiment.

**Experiment IA(k).**

1. (*Initialization Phase*) Simulator  $\mathcal{S}$  invokes  $\text{Init}$ ,  $\text{GKg}$ , invokes  $\text{UKg}$  (resp.  $\text{Join}, \text{lss}$ )  $g_u \geq 2$  times to generate a set of joined users, with their extended user public keys  $xpk_{\text{id}}$ ’s.
2. (*Probe-1 Phase*)  $\mathcal{A}$  queries  $\mathcal{GCO}$ ,  $\mathcal{AUO}$ ,  $\mathcal{CO}$ ,  $\mathcal{JO}$ ,  $\mathcal{H}$ ,  $\mathcal{SO}_k$  in arbitrary interleaf.
3. (*Gauntlet Phase*)  $\mathcal{A}$  selects a gauntlet group  $\text{cnt}_{ga}$ , two members who have joined this group, denoted *gauntlet users*  $\text{id}_0, \text{id}_1$ , a gauntlet verifier  $\text{bsn}_{ga}$ , and a message  $M$  for  $\mathcal{S}$ . Then  $\mathcal{S}$  flips a fair coin  $b \in \{0, 1\}$  and returns the *gauntlet signature*  $\sigma_{ga} = \text{GSig}(\text{id}_b, \text{cnt}_{ga}, xsk_{\text{id}_b, \text{cnt}_{ga}}, \text{bsn}_{ga}, M)$ .
4. (*Probe-2 Phase*)  $\mathcal{A}$  queries  $\mathcal{GCO}$ ,  $\mathcal{AUO}$ ,  $\mathcal{CO}$ ,  $\mathcal{JO}$ ,  $\mathcal{H}$ ,  $\mathcal{SO}_k$  in arbitrary interleaf.
5. (*End Game*)  $\mathcal{A}$  delivers an estimate  $\hat{b} \in \{0, 1\}$  of  $b$ .

$\mathcal{A}$  wins Experiment IA(k) if  $\hat{b} = b$ , it has queried  $\mathcal{SO}_k(\text{id}, \text{cnt}_{ga}, \text{bsn}_{ga}, M')$  no more than  $k - 1$  times with  $\text{id} = \text{id}_0$  (resp.  $\text{id} = \text{id}_1$ ), and it has never queried  $\mathcal{CO}(\text{id}_0, \text{cnt}_{ga})$  or  $\mathcal{CO}(\text{id}_1, \text{cnt}_{ga})$ . The restriction on  $\mathcal{SO}_k$  queries is trivially necessary because the TbL mechanism together with enough such  $\mathcal{SO}_k$  queries wins Experiment IA(k) outright.  $\mathcal{A}$ ’s *advantage* in Experiment IA(k) is its probability of winning, minus half. Oracle queries can be arbitrarily interleaved across Probe-1, Gauntlet, and Probe-2 Phases.

**Definition 2 (Irrevocable k-Anonymity).** An TbL group signature is irrevocably  $k$ -anonymous if no PPT algorithm has a non-negligible advantage in Experiment IA(k). When  $k = 1$ , it is irrevocably anonymous.

*Remark:* The irrevocable anonymity is a kind of computational zero-knowledge about the signer identity. In comparison, some stronger anonymity models in ring signatures allow  $\mathcal{A}$  to corrupt the gauntlet users, and/or achieve statistical zero-knowledge. On the other hand, irrevocable anonymity allows  $\mathcal{A}$  to corrupt all authorities while many TbE group signature models do not.

**The  $k$ -linkability, the full  $k$ -linkability.** Roughly speaking, full  $k$ -linkability means that any coalition of  $q_{\ell}$  corrupted users, without the group manager, cannot produce  $kq_{\ell} + 1$  valid signatures for the same  $(\text{cnt}, \text{bsn})$  that are not linked to any colluder. The case  $q_{\ell} = 0$  corresponds to unforgeability of the signature, and the case  $q_{\ell} = 1$  corresponds to  $k$ -linkability. Formally, Full  $k$ -Linkability is defined in terms of the following experiment.

**Experiment FL( $k$ ).**

1. (*Initialization Phase*)  $\mathcal{S}$  invokes  $\text{Init}$ ,  $\text{GKg}$ , invokes  $\text{UKg}$  (resp.  $\text{Join}, \text{Iss}$ ) a polynomially many times.
2. (*Probe-1 Phase*)  $\mathcal{A}$  makes  $q_G$  (resp.  $q_A, q_C, q_J, q_H, q_S$ ) queries to  $\mathcal{GCO}$  (resp.  $\mathcal{AUO}, \mathcal{CO}, \mathcal{JO}, \mathcal{H}, \mathcal{SO}_k$ ) in arbitrary interleaf.
3.  $\mathcal{A}$  delivers  $\text{cnt}$ ,  $\text{bsn}$ , and signatures  $\sigma_i$  for  $1 \leq i \leq k(q_J + \hat{q}_C) + 1$ , where  $\text{cnt}$  has never been queried to  $\mathcal{GCO}$ , each the signatures satisfies  $\text{GVf}(\sigma_i, \text{cnt}, \text{bsn}) = 1$  and is not the output of an  $\mathcal{SO}_k$  query, and  $\hat{q}_C$  is the total number of  $\text{Join}$ 's by all users created in the Initialization Phase and corrupted by querying  $\mathcal{CO}$ .

$\mathcal{A}$  wins Experiment FL( $k$ ) if  $\text{Link}(\sigma_{i_1}, \dots, \sigma_{i_{k+1}})$  does not output any of the corrupted users for arbitrary  $1 \leq i_1 < \dots < i_{k+1} \leq k(q_J + \hat{q}_C) + 1$ .  $\mathcal{A}$ 's *advantage* is its probability of winning.

**Definition 3 (Full  $k$ -Linkability).** A TbL group signature is fully  $k$ -linkable if no PPT algorithm has a non-negligible advantage in Experiment FL( $k$ ). It is fully linkable in the case  $k = 1$ .

**Non-slanderability** In a nutshell, non-slanderability means a coalition of users together with the group manager cannot produce signatures that are linked and indicted to a group member outside the coalition. Formally,

**Experiment NS( $k$ )**

1.  $\mathcal{S}$  invokes  $\text{Init}$ ,  $\text{GKg}$ , invokes  $\text{UKg}$  (resp.  $\text{Join}, \text{Iss}$ ) a polynomially many times.
2.  $\mathcal{A}$  queries  $\mathcal{GCO}, \mathcal{AUO}, \mathcal{CO}, \mathcal{JO}, \mathcal{H}, \mathcal{SO}_k$  in arbitrary interleaf.
3.  $\mathcal{A}$  delivers  $k+1$  valid signatures,  $\sigma_i, 1 \leq i \leq k+1$ , such that  $\text{Link}(\sigma_1, \dots, \sigma_{k+1}) = 1$ , and  $\text{Indict}(\sigma_1, \dots, \sigma_{k+1}) = \text{id}$  where  $\text{id}$  has never been queried to  $\mathcal{CO}$ .

$\mathcal{A}$  wins Experiment NS( $k$ ) if it completes. Its *advantage* is his probability of winning.

**Definition 4 ( $k$ -Non-Slanderability).** A TbL group signature is  $k$ -non-slanderable if no PPT adversary has a non-negligible advantage in Experiment NS( $k$ ). It is non-slanderable in the case  $k=1$ .

Summarizing, we have:

**Definition 5 (Security).** A TbL group signature is  $k$ -secure if it is correct, irrevocably  $k$ -anonymous, fully  $k$ -linkable, and  $k$ -non-slanderable. It is secure in the case  $k = 1$ .

*Remark:* There is a slightly weaker security model, the *SbV-secure TbL group signature* where SBV stands for *Slanderable-but-Vindicatable*. It is otherwise secure like secure TbL group signatures, except it allows the indictment of some non-guilty users who can subsequently *vindicate* themselves via an additional Protocol *Vindicate*. Only those who are indicted but cannot vindicate themselves are truly guilty. We exhibit a SbV-secure TbL group signature in Appendix A of the full paper [40].

*Related security notions.* Exculpability (cf. misidentification attack [25]) of TbE group signature means that a coalition of users, together with the group manager (and the open authority) cannot produce a signature traced to an uncorrupted member. The TbL group signature does not have the "open signature" functionality of TbE group signatures, and the notion of exculpability is, in a sense, absorbed into non-slanderability. Non-slanderability implies that the *indictment* is accurate: If user  $\text{id}_g$  is indicted, then non-slanderability implies no one except  $\text{id}_g$  could have generated the double signing.

### 3 Preliminaries

We say  $N$  is a *safe product* if  $N = pq$ ,  $p = 2p' + 1$ ,  $q = 2q' + 1$ ,  $p, q, p',$  and  $q'$  are sufficiently large primes. The set of *quadratic residues* in  $Z_N$ , denoted  $QR_N$ , consists of all squares in  $Z_N$ .

**Strong RSA Assumption** There exists no PPT algorithm which, on input a random  $\lambda_s$ -bit safe product  $N$  and a random  $z \in QR_N$ , returns  $u \in \mathbb{Z}_N^*$  and  $e \in \mathbb{N}$  such that  $e > 1$  and  $u^e = z \pmod{N}$ , with non-negligible probability and in time polynomial in  $\lambda_s$ .

We will need the DDH (Decisional Diffie-Hellman) Assumption across two groups, with possibly different orders: Let  $G_a$  and  $G_b$  be two groups. The **DDH( $G_a, G_b$ ) Problem** is, given random  $g, g^\alpha \in G_a$  and  $h \in G_b$ , distinguish  $h^\alpha$  from random, where  $0 < \alpha < \min\{\text{order}(G_a), \text{order}(G_b)\}$ . The **DDH( $g_a, g_b$ ) Assumption** is that no PPT algorithm can solve the DDH( $G_a, G_b$ ) Problem with non-negligible probability.

**The  $q$ -Strong Diffie-Hellman ( $q$ -SDH) Assumptions** Let  $e : G_1 \times G_2 \rightarrow G_3$  be a pairing, with  $q_i = \text{order}(G_i)$ ,  $1 \leq i \leq 3$ . The  *$q$ -Strong Diffie-Hellman Problem ( $q$ -SDH)* is the problem of computing a pair  $(g_1^{1/(\gamma+x)}, x)$  given  $(g_1 \in G_1, g_2, g_2^\gamma, g_2^{\gamma^2}, \dots, g_2^{\gamma^q} \in G_2)$ , and a homomorphism  $\psi(g_2) = g_1$ . The  *$q$ -SDH Assumption* is that no PPT algorithm has a non-negligible probability of solving a random sample of the  $q$ -SDH Problem. For further details, see [7].

Related is the  **$q$ -CAA (Coalition Attack Algorithm) Assumption** [31, 42], that no PPT algorithm can solve the  $q$ -CAA Problem: Given random  $g_2, g_2^\gamma \in G_2$ , and pairs  $(A_i, e_i)$  with distinct and nonzero  $e_i$ 's satisfying  $A_i^{\gamma+e_i} = v$ ,  $1 \leq i \leq q$ , compute a pair  $(A_{q+1}, e_{q+1})$  with  $e_{q+1} \neq e_i$  for any  $i$ ,  $1 \leq i \leq q$ , and satisfying  $A_{q+1}^{\gamma+e_{q+1}} = v$ . Appendix B contains several equivalence reductions among the  $q$ -SDH Assumption, the  $q$ -CAA Assumption, and some other related assumptions.

## 4 Constructing TbL Group Signatures

We construct two TbL group signatures in pairings and in the strong RSA framework, respectively. The former signature is typically short, but involves expensive pairings computation by the Verifier. The latter signature is typically fast, but not as short as the former signature. The constructions in this Section has  $k=1$ . Constructions with  $k > 1$  are discussed in the next Section. Also, for simplicity, we assume there is only one group cnt and thus omit the group index from the notations.

### 4.1 Generic construction: intuitions

We describe the intuition of our constructions in a loosely specific generic construction.

The user sk-pk pair is  $((x_1, x_2, x_3, x_4), \text{PedCom}(x_1, x_2, x_3; x_4))$ , where **PedCom** is Pedersen's commitment [34], and  $x_1 = U$  is the user identity. The group membership certificate is  $\text{cert} = \text{Sign}_{gsk}(\text{PedCom}(x_1, x_2, x_3; x_4))$ , where **Sign** is a signature by the Group Manager, i.e. the group certificate issuer. The group signature is the following signature proof-of-knowledge (SPK):

$$\begin{aligned} \sigma = SPK\{ & (x_1, x_2, x_3, x_4, \text{cert}) : \text{cert} = \text{Sign}_{gsk}(\text{PedCom}(x_1, x_2, x_3; x_4)) \\ & \wedge z = x_2 - cx_1 \text{ where } c \text{ is the challenge of this SPK } \wedge \text{serial} = \mathbf{g}^{x_3}\}(\text{param}, \text{nonce}, M) \end{aligned} \quad (1)$$

The group signature verifier, Protocol **GVf**, verifies the proof  $\sigma$ . Protocol **Link** outputs 1=linked if and only if two valid input signatures have the same **serial**. Protocol **Indict** outputs the signer identity  $u = x_1$  computed from the following linear equations:  $z = x_2 - cx_1$  and  $z' = x_2 - c'x_1$ , respectively, from two linked signatures.

The intuition in the security analysis is as follows: The anonymity comes the perfect statistical hiding property of Pedersen commitments. The full linkability and the non-slanderability are straightforward.

### 4.2 Instantiating in strong RSA: Protocol TbL-SRSA

We construct a TbL group signature in the strong RSA framework [2, 14].

**Protocols Init, GKg:** Given security parameter  $1^{\lambda_s}$ , initializes additional security parameters  $\epsilon > 1$ ,  $\ell_p$ ,  $\lambda_1$ ,  $\lambda_2$ ,  $\gamma_1$ ,  $\gamma_2$  satisfying  $\lambda_1 > \epsilon(\lambda_2 + \lambda_s) + 3$ ,  $\lambda_2 > 4\ell_p$ ,  $\gamma_1 > \epsilon(\gamma_2 + \lambda_s) + 3$ , and  $\gamma_2 > \lambda_1 + 3$ . Note  $\ell_p$  sets the size of the modulus of the RSA framework,  $\epsilon$  controls the tightness of the zero-knowledge [2]. Generate a product  $N$  of two  $\ell_p$ -bit safe primes  $p$  and  $q$ , i.e.  $p = 2p' + 1$ ,  $q = 2q' + 1$ ,  $p'$  and  $q'$  are both primes. Generate a known-order group  $G_S = \langle \mathbf{g} \rangle$ , where  $\text{order}(G_S) = p_s$  which is a  $(\gamma_1 + 1)$ -bit prime. The signature-signing group sk-pk pair is  $((p, q), N)$ . Generates a user list  $UL$  which is initially empty. Let all discrete logarithm bases be fairly generated, e.g.  $g_i = \mathcal{H}('g', i) \in QR_N$ ,  $h_i = \mathcal{H}('h', i) \in QR_N$ ,  $\mathbf{g}_i = \mathcal{H}('g', i) \in G_S$ . We adopt the flexible notation  $\mathcal{H}$  which is a full-domain collision-resistant hash function mapping from a union of mixed domains to a union of mixed ranges. Ambiguity should not arise from the context. Denote the intervals  $\Gamma = ]2^{\lambda_1} - 2^{\lambda_2}, 2^{\lambda_1} + 2^{\lambda_2}[$  and  $\Gamma = ]2^{\gamma_1} - 2^{\gamma_2}, 2^{\gamma_1} + 2^{\gamma_2}[$ .

**Protocols Join, lss:** accepts common inputs  $\text{id}$ , Join's additional input  $\text{usk}_{\text{id}}$ , lss's additional input  $\gamma$  and proceed as follows:

1. Protocol Join identifies itself as User  $\text{id}$  with knowledge of  $\text{usk}_{\text{id}}$ , and then randomly generates  $x'_2, x'_3, x'_4 \in ]-2^{\lambda_2-1}, 2^{\lambda_2-1}[$ , with  $x'_1 = \text{id} \cdot x'_2$ . Presents  $h_1^{x'_1}, h_2^{x'_2}, h_3^{x'_3}, h_4^{x'_4}$ . Prove knowledge of their discrete logarithms. Prove their range  $x'_2, x'_3, x'_4 \in ]-2^{\lambda_2-1}, 2^{\lambda_2-1}[$ , and prove  $x'_1 = \text{id} \cdot x'_2$ .
2. Protocol lss verifies the proofs; randomly generates  $x''_2, x''_3, x''_4 \in ]-2^{\lambda_2-1}, 2^{\lambda_2-1}[$  with  $x''_1 = \text{id} \cdot x''_2$ ; gives them and a certificate  $(A, e)$  satisfying  $A^e h_1^{x''_1} h_2^{x''_2} h_3^{x''_3} h_4^{x''_4} = h_0$  to Protocol Join, where  $x_i = 2^{\lambda_1} + x'_i + x''_i \in \Lambda$ ,  $1 \leq i \leq 4$ , and  $e \in \Gamma$  is a prime. Then Protocol lss inserts the entry  $(\text{id}, \text{xpk} = (h_1^{x''_1}, h_2^{x''_2}, h_3^{x''_3}, h_4^{x''_4}), \text{cert} = (A, e))$  into  $UL$  which is considered part of the public  $\text{param}$ .

For simplicity, assume each  $x'_i$  (resp.  $x''_i$ ) is even so all user public keys are in  $QR_N$ .

**Protocol GSig**( $\text{id}, \text{xsk}_{\text{id}} = (A, e, x_1, x_2, x_3, x_4)$ ,  $\text{bsn}, M$ ): It outputs signature  $\sigma$  which is a signature proof of knowledge (non-interactive zero-knowledge proof-of-knowledge) of the following proof system (range check on  $e$  is omitted for simplicity)

$$\begin{aligned} & \text{SPK}\{\{(A, e, x_1, x_2, x_3, x_4) : \\ & A^e h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} = h_0 \in QR_N \wedge x_3 = cx_1 + z \wedge x_4 = cx_2 + z' \\ & \wedge c \text{ is the challenge of this proof system}\}(\text{param}, \text{nonce}, \text{bsn}, M) \end{aligned}$$

Further instantiation details of GSig are below: The commitments are

$$\begin{aligned} T_0 &= g_0^{s_0}, \quad T_A = Ag_A^{s_0}, \quad [\text{Note } h_0 = T_A^e h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} g_A^{-s_1} \text{ where } s_1 = es_0, \\ & \text{and } 1 = T_0^e g_0^{-s_1}] \quad T_e = g_{e,1}^e g_{e,2}^{s_0}, \quad T_2 = g_{2,1}^{x_2} g_{2,2}^{s_0}, \quad T_3 = g_{3,1}^{x_3} g_{3,2}^{s_0}, \quad T_4 = g_{4,1}^{x_4} g_{4,2}^{s_0}, \\ D_0 &= g_0^{r_0}, \quad D_A = T_A^{r_e} h_1^{r_{x,1}} h_2^{r_{x,2}} h_3^{r_{x,3}} h_4^{r_{x,4}} g_A^{-r_1}, \quad D_1 = T_0^{r_e} g_0^{-r_1}, \quad D_e = g_{e,1}^{r_e} g_{e,2}^{r_0}, \\ D_2 &= g_{2,1}^{r_{x,2}} g_{2,2}^{r_0}, \quad D_3 = g_{3,1}^{r_{x,3}} g_{3,2}^{r_0}, \quad D_4 = g_{4,1}^{r_{x,4}} g_{4,2}^{r_0}, \quad T_5 = \mathbf{g}_{\text{bsn},1}^{x_1}, \quad T_6 = \mathbf{g}_{\text{bsn},2}^{x_2}, \\ T_7 &= \mathbf{g}_{\text{bsn},1}^{x_3}, \quad T_8 = \mathbf{g}_{\text{bsn},2}^{x_4}, \quad D_5 = T_7, \quad D_6 = T_8, \quad D_7 = \mathbf{g}_{\text{bsn},1}^{r_{x,3}}, \quad D_8 = \mathbf{g}_{\text{bsn},2}^{r_{x,4}}, \end{aligned} \quad (2)$$

Note  $r_{x,1} = x_3$ ,  $r_{x,2} = x_4$ . The challenge is:

$$\begin{aligned} c &= \mathcal{H}(\text{param}, \text{nonce}, \text{bsn}, M, T_0, T_A, T_e, \\ & T_2, T_3, T_4, T_5, T_6, D_0, D_A, D_e, D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8) \end{aligned} \quad (3)$$

The responses are:

$$z_e = r_e - ce, \quad z_0 = r_0 - cs_0, \quad z_1 = r_1 - cs_1, \quad z_{x,i} = r_{x,i} - cx_i, \quad 1 \leq i \leq 4.$$

The signature is:

$$\begin{aligned} \sigma &= (\text{param}, \text{nonce}, \text{bsn}, M, T_0, T_A, T_e, \\ & T_2, T_3, T_4, T_5, T_6, c, z_e, z_0, z_1, z_{x,1}, z_{x,2}, z_{x,3}, z_{x,4}) \end{aligned}$$

**Protocol**  $\text{GVf}(\sigma)$  parses the input, computes

$$\begin{aligned} D_0 &= g_0^{z_0} T_0^c, & D_A &= T_A^{z_e} h_1^{z_{x,1}} h_2^{z_{x,2}} h_3^{z_{x,3}} h_4^{z_{x,4}} g_A^{-z_1} T_A^c, & D_1 &= T_0^{z_e} g_0^{-z_1}, \\ D_e &= g_{e,1}^{z_e} g_{e,2}^{z_0} T_e^c, & D_2 &= g_{2,1}^{z_{x,2}} g_{2,2}^{z_0} T_2^c, & D_3 &= g_{3,1}^{z_{x,3}} g_{3,2}^{z_0} T_3^c, & D_4 &= g_{4,1}^{z_{x,4}} g_{4,2}^{z_0} T_4^c, \\ D_5 &= \mathbf{g}_{\text{bsn},1}^{z_{x,1}} T_5^c, & D_6 &= \mathbf{g}_{\text{bsn},2}^{z_{x,2}} T_6^c, & D_7 &= \mathbf{g}_{\text{bsn},1}^{z_{x,3}} D_5^c, & D_8 &= \mathbf{g}_{\text{bsn},2}^{z_{x,4}} D_6^c \end{aligned}$$

Verifies that the challenge  $c$  computed from Equation (3) equals to that parsed from the input in order to output 1.

**Protocol**  $\text{Link}(\sigma, \sigma')$ : Verifies the validity of both input signatures. Parses both signatures. Outputs 1 if  $T_5 = T'_5$ , and outputs 0 otherwise.

**Protocol**  $\text{Indict}(\sigma, \sigma')$ : Verifies the validity of both input signatures. Parses both signatures. Solves  $x_1$  from  $x_3 = cx_1 + z_{x,1}$  and  $x_3 = c'x_1 + z'_{x,1}$ . Solves  $x_2$  similarly. Outputs  $\text{id} = x_1/x_2$ .

The following Theorem analyzes the security of Protocol TbL-SRSA.

**Theorem 1.** *Let  $N$  be a product of two safe primes. Protocol TbL-SRSA is a TBL group signature which, assuming the Random Oracle (RO) model,*

1. *is correct;*
2. *is irrevocably anonymous under the DDH Assumption in  $QR_N$ ;*
3. *is fully linkable under the strong RSA Assumption;*
4. *is non-slanderable provided Discrete Logarithm is hard in  $QR_N$ .*

*In summary, Protocol TbL-SRSA is a secure TbL group signature provided the DDH Assumption and the strong-RSA Assumption both hold in  $QR_N$ .*

**4.2.1 Protocol TbL-SRSA2: with higher indictment complexity.** Another TbL group signature, which we call *Protocol TbL-SRSA2*, can be modified from Protocol TbL-SRSA above by replacing the commitments  $T_5, T_6, T_7, T_8, D_5, D_6, D_7, D_8 \in G_S$  in Equation (2) by

$$T_5 = g_{\text{bsn},1}^{x_1}, \quad T_6 = g_{\text{bsn},2}^{x_2}, \quad T_7 = g_{\text{bsn},1}^{x_3}, \quad T_8 = g_{\text{bsn},2}^{x_4}, \quad D_5 = T_7, \quad D_6 = T_8, \quad D_7 = g_{\text{bsn},1}^{r_{x,3}}, \quad D_9 = g_{\text{bsn},2}^{r_{x,4}} \quad (4)$$

where  $g_{\text{bsn},1}, g_{\text{bsn},2} \in QR_N$ . The rest of Protocols  $\text{GSig}, \text{GVf}, \text{Link}$  remain.

The Protocol  $\text{Indict}(\sigma, \tilde{\sigma})$  is modified as follows: Verify  $\sigma$  and  $\tilde{\sigma}$  are valid signatures, and linked. Parse the two signatures and computer to obtain  $\tau = (\tilde{c} - c)x_1$ . Test  $h_1^\tau$  against all listed user public key  $(h_1^{x_1}, \dots, h_4^{x_4})$  in  $UL$  for a match, and output the matched  $\text{id}$ .

Note the computation complexity of this  $\text{Indict}$  protocol is proportional to the number of listed users, whereas the complexity of TbL-SRSA's  $\text{Indict}$  is  $O(1)$ . But indictment should be a rare event.

The reductionist security of Protocol TbL-SRSA2 is essentially the same as that of Protocol TbL-SRSA.

*No longer need a known-order group:* Note in Protocol TbL-SRSA2, we can set  $G_S = QR_N$ , a group with unknown order. By using an unknown-order group, the computation of the exact value of  $x_1$  and  $x_2$  cannot be completed at all times. But by using the more complex  $\text{Indict}$  Protocol above, we can still complete the indictment at all times with negligible exceptions.

### 4.3 Another instantiation in strong RSA: Protocol TbL-SRSA-PC

We construct another TbL group signature in the strong RSA framework [2, 14].

**Protocols**  $\text{Init}, \text{GKg}$ : Given security parameter  $1^{\lambda_s}$ , initializes additional security parameters  $\epsilon > 1, \ell_p, \lambda_1, \lambda_2, \gamma_1, \gamma_2$  satisfying  $\lambda_1 > \epsilon(\lambda_2 + \lambda_s) + 3, \lambda_2 > 4\ell_p, \gamma_1 > \epsilon(\gamma_2 + \lambda_s) + 3$ , and  $\gamma_2 > \lambda_1 + 3$ . Note  $\ell_p$  sets the size of the modulus of the RSA framework,  $\epsilon$  controls the tightness of the zero-knowledge [2]. Generate a product  $N$  of two  $\ell_p$ -bit safe primes  $p$  and  $q$ , i.e.  $p = 2p' + 1, q = 2q' + 1, p'$  and  $q'$  are both primes. Generate a known-order group  $G_S = \langle \mathbf{g} \rangle$ , where  $\text{order}(G_S) = p_s$  which is a  $(\gamma_1 + 1)$ -bit prime. The signature-signing group  $\text{sk-pk}$  pair is  $((p, q), N)$ . Generates a user list  $UL$  which is initially empty and always honestly maintained. Let all discrete logarithm bases be fairly generated, e.g.  $g_i = \mathcal{H}(g', i) \in QR_N, h_i = \mathcal{H}(h', i) \in QR_N$ ,

$\mathbf{g}_i = \mathcal{H}(\mathbf{g}', i) \in G_S$ . We adopt the flexible notation  $\mathcal{H}$  which is a full-domain collision-resistant hash function mapping from a union of mixed domains to a union of mixed ranges. Ambiguity should not arise from the context. Denote the intervals  $\Gamma = ]2^{\lambda_1} - 2^{\lambda_2}, 2^{\lambda_1} + 2^{\lambda_2}[$  and  $\Gamma = ]2^{\gamma_1} - 2^{\gamma_2}, 2^{\gamma_1} + 2^{\gamma_2}[$ .

**Protocols Join, lss:** accepts common inputs  $\text{id}$ , Join's additional input  $\text{usk}_{\text{id}}$ , lss's additional input  $\gamma$  and proceed as follows:

1. Protocol Join authenticates itself as User  $\text{id}$ . It is required that  $\text{id} \in \Lambda$ . Then it sets  $x_1 = \text{id}$  and randomly generates  $x'_i \in ] - 2^{\lambda_2-1}, 2^{\lambda_2-1}[$  for  $2 \leq i \leq 6$ . Presents  $\text{upk}_{\text{id}} = h_1^{x_1} h_2^{x'_2} h_3^{x'_3} h_4^{x'_4} h_5^{x'_5} h_6^{x'_6}$ . Prove knowledge of  $x'_2, x'_3, x'_4, x'_5, x'_6 \in ] - 2^{\lambda_2-1}, 2^{\lambda_2-1}[$ , and  $x_1 = \text{id}$ .
2. Protocol lss verifies the proofs; randomly generates  $x''_2, x''_3, x''_4, x''_5, x''_6 \in ] - 2^{\lambda_2-1}, 2^{\lambda_2-1}[$ ; creates a certificate  $(A, e)$  satisfying  $A^e h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} h_5^{x_5} h_6^{x_6} = h_0$  for Protocol Join, where  $x_i = 2^{\lambda_1} + x'_i + x''_i \in \Lambda$ ,  $i = 2, 3, 4, 5, 6$ , and  $e \in \Gamma$  is a prime. Then Protocol lss inserts the entry  $(\text{id}, \text{xp}k = h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} h_5^{x_5} h_6^{x_6}, \text{cert} = (A, e))$  into  $UL$  which is considered part of the public  $\text{param}$ .

For simplicity, assume each  $x'_i$  (resp.  $x''_i$ ) is even so all user public keys are in  $QR_N$ .

**Protocol GSig**( $\text{id}, \text{xsk}_{\text{id}} = (A, e, x_1, x_2, x_3, x_4, x_5, x_6), M$ ): It outputs signature  $\sigma$  which is a signature proof of knowledge (non-interactive zero-knowledge proof-of-knowledge) of the following proof system: (Range checks are omitted for simplicity. For details see Boudot [8].)

$$\begin{aligned} SPK\{ & \{(A, e, x_1, x_2, x_3, x_4, x_5, x_6) : A^e h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} h_5^{x_5} h_6^{x_6} = h_0 \in QR_N \wedge z_1 = x_2 - cx_1 \\ & \wedge z_3 = x_4 - cx_3 \wedge z_5 = x_6 - cx_5 \text{ where } c \text{ is the challenge of this proof} \wedge S = h_{\text{bsn}}^{x_4}\}(\text{param}, \text{nonce}, M) \end{aligned}$$

Further instantiation details of GSig are below: The commitments are

$$\begin{aligned} T_0 &= g_0^{s_0}, \quad T_A = Ag_A^{s_0}, \quad [\text{Note } h_0 = T_A^e h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} h_5^{x_5} h_6^{x_6} g_A^{-s_1} \text{ where } s_1 = es_0, \text{ and } 1 = T_0^e g_0^{-s_1}] \\ T_e &= g_{e,1}^{s_0}, \quad T_2 = g_{2,1}^{s_0}, \quad T_3 = g_{3,1}^{s_0}, \quad T_4 = g_{4,1}^{s_0}, \quad T_5 = g_{5,1}^{s_0}, \quad T_6 = g_{6,1}^{s_0}, \quad S = h_{\text{bsn}}^{x_3}, \\ D_0 &= g_0^{r_0}, \quad D_A = T_A^{r_e} g_A^{-r_1} \prod_{1 \leq i \leq 6} h_i^{r_{x,i}}, \quad D_1 = T_0^{r_e} g_0^{-r_1}, \quad D_e = g_{e,1}^{r_e}, \\ D_2 &= g_{2,1}^{r_{x,2}} g_{2,2}^{r_0}, \quad D_3 = g_{3,1}^{r_{x,3}} g_{3,2}^{r_0}, \quad D_4 = g_{4,1}^{r_{x,4}} g_{4,2}^{r_0}, \quad D_5 = g_{5,1}^{r_{x,5}} g_{5,2}^{r_0}, \quad D_6 = g_{6,1}^{r_{x,6}} g_{6,2}^{r_0}, \quad D_s = h_{\text{bsn}}^{r_{x,3}}, \\ T_7 &= \mathbf{g}_7^{x_1} \mathbf{g}_8^{s_3}, \quad T_8 = \mathbf{g}_7^{x_2} \mathbf{g}_8^{s_4}, \quad D_7 = \mathbf{g}_7^{r_{x,1}} \mathbf{g}_8^{r_3}, \quad D_8 = \mathbf{g}_7^{r_{x,2}} \mathbf{g}_8^{r_4}, \quad T_9 = \mathbf{g}_9^{x_3} \mathbf{g}_{10}^{s_5}, \quad T_{10} = \mathbf{g}_9^{x_4} \mathbf{g}_{10}^{s_6}, \\ D_9 &= \mathbf{g}_9^{r_{x,3}} \mathbf{g}_{10}^{r_5}, \quad D_{10} = \mathbf{g}_9^{r_{x,4}} \mathbf{g}_{10}^{r_6}, \quad T_{11} = \mathbf{g}_{11}^{x_5} \mathbf{g}_{12}^{s_7}, \quad T_{12} = \mathbf{g}_{11}^{x_6} \mathbf{g}_{12}^{s_8}, \quad D_{11} = \mathbf{g}_{11}^{r_{x,5}} \mathbf{g}_{12}^{r_7}, \quad D_{12} = \mathbf{g}_{11}^{r_{x,6}} \mathbf{g}_{12}^{r_8}, \end{aligned} \quad (5)$$

where  $r_{x,1} = x_2, r_{x,3} = x_4, r_{x,5} = x_6, r_3 = s_4, r_5 = s_6, r_7 = s_8$  and therefore  $D_7 = T_8, D_9 = T_{10}, D_{11} = T_{12}$ . The challenge is:

$$\begin{aligned} c &= \mathcal{H}(\text{param}, \text{nonce}, M, T_0, T_A, T_e, \\ & T_2, \dots, T_{12}, S, D_0, D_A, D_e, D_1, \dots, D_{12}) \end{aligned} \quad (6)$$

The responses are:

$$z_e = r_e - ce, \quad z_i = r_i - cs_i \text{ for } 0 \leq i \leq 8, \quad z_{x,i} = r_{x,i} - cx_i \text{ for } 1 \leq i \leq 6.$$

The signature is:

$$\begin{aligned} \sigma &= (\text{param}, \text{nonce}, M, T_0, T_A, T_e, S, \\ & T_2, \dots, T_{12}, c, z_e, z_0, \dots, z_8, z_{x,1}, \dots, z_{x,6}) \end{aligned}$$

**Protocol GVf**( $\sigma$ ) is straightforward and omitted.

**Protocol Link**( $\sigma, \sigma'$ ): Verifies the validity of both input signatures. Parses the inputs into  $\sigma = (\dots, S, \dots)$  and  $\sigma' = (\dots, S', \dots)$ . Outputs 1=linked if  $S = S'$ , and outputs 0 otherwise.

**Protocol Indict**( $\sigma, \sigma'$ ): Verifies the validity of both input signatures. Parses both signatures. Solves  $x_1, \dots, x_6$  in  $(\text{mod } p_s)$  where  $p_s$  is the (known) order of the group  $G_S$ . Confirm the range: that  $x_1, \dots, x_6 \in \Lambda$ . Set  $\text{id} = x_1$ . Confirm  $\text{xsk}_{\text{id}} = \prod_{i=1}^6 h_i^{x_i}$ . Output  $\text{id}$ .

The following Theorem analyzes the security of Protocol TbL-SRSA-PC.



**Theorem 2.** *Protocol TbL-SRSA-PC is a TBL group signature with  $k = 1$  which, assuming the Random Oracle (RO) model,*

1. *is correct;*
2. *is irrevocably anonymous;*
3. *is fully linkable under the strong RSA Assumption;*
4. *is non-slanderable provided Discrete Logarithm is hard in  $QR_N$ .*

*In summary, Protocol TbL-SRSA-PC is a secure TBL group signature provided the strong-RSA Assumption and the DDH Assumption both hold in  $QR_N$  in the RO model.*

*Proof Sketch:* Correctness is straightforward. Noting the user public key  $xpk = \text{PedCom}(x_1, x_2, x_3, x_4, x_5; x_6)$  is a Pedersen commitment [34], our irrevocable anonymity follows from the *perfect statistical hiding* property of Pedersen commitments. Noting our group signature proof system in Equation (7) proves more relations than the group signature proof system of Ateniese, et al. [2], our full linkability follows from a proof similar to [2]’s proof of full traceability. By the same token, our non-slanderability follows the no-frameability of [2].

One extra point worth additional attention is our simulation of the Signing Oracle  $\mathcal{SO}(\text{id}, \text{cnt}, M)$ . It is simulated as follows:

1. Retrieve user public key  $xpk_{\text{id}}$  from the user database  $UL$ .
2. Randomly generate the challenge  $c$ .
3. Randomly generate  $z_{x,1}, z_1, T_1$ , and compute  $D_1$ .
4. Set  $T_2 = D_1$ .
5. Randomly generate the remaining responses  $z_{x,i}$  for  $2 \leq i \leq 4$ ,  $z_i$  for  $0 \leq i \leq 2$ ,  $S$ , and  $T_A$ . Compute  $D_0, D_2, D_3$ . Backpatch the random oracle in Equation (8).

It can be shown that this simulation is indistinguishable from the real world Protocol GSig.  $\square$

*Post-indictment framing:* After an indictment of a user  $\text{id}$  in Protocol TbL-SRSA-PC, the Group Manager can produce more TbL group signatures that are linked and indicted to  $\text{id}$ . This can be viewed as a vulnerability. Best to do is to construct a TbL group signature that does not have this vulnerability.

#### 4.4 Instantiating in pairings: Protocol TbL-SDH-PC

We construct a TbL group signature in pairings [31, 42, 6, 7], and reduce its security to intractability assumptions.

**Init, GKg:** Generate a pairing  $\hat{e} : G_1 \times G_2 \rightarrow G_T$ . Generate all discrete logarithm bases fairly, e.g.  $g_i = \mathcal{H}('g', i) \in G_1$ ,  $\mathbf{g} = \mathcal{H}('g', i) \in G_T$ ,  $h_i = \mathcal{H}('h', i) \in G_1$ ,  $u_i = \mathcal{H}('u', i) \in G_2$ . The group sk-pk pair is  $(\gamma, u^\gamma)$ . Generates a user list  $UL$  which is initially empty. We adopt the flexible notation  $\mathcal{H}$  that it is a full-domain cryptographically secure hash function mapping from a union of mixed domains to a union of mixed ranges. Ambiguity should not arise from the context.

**UKg:** On input  $\text{id}$ , sample the relation  $\mathcal{R}_{\text{user}}$  to output  $(usk_{\text{id}}, upk_{\text{id}})$ .

**Protocols Join, lss:** accepts common inputs  $\text{id}$ , Join’s additional input  $usk_{\text{id}}$ , lss’s additional input  $\gamma$  and proceed as follows:

1. Protocol Join identifies itself as User  $\text{id}$  with knowledge of  $usk_{\text{id}}$ , and then sets  $x_1 = \text{id}$  and randomly generates  $x'_i$  for  $2 \leq i \leq 6$ . Presents  $upk_{\text{id}} = h_1^{x_1} \prod_{i=2}^6 h_i^{x'_i}$ ; proves knowledge of  $x'_i$ ,  $1 \leq i \leq 6$  and  $x_1 = \text{id}$ .
2. Protocol lss verifies the proofs; randomly generates  $x''_i$  for  $2 \leq i \leq 6$ ; gives them and a certificate  $(A, e)$  satisfying  $A^{e+\gamma} \prod_{i=1}^6 h_i^{x_i} = h_0 \in G_1$  to Protocol Join, where  $x_i = x'_i + x''_i$ ,  $2 \leq i \leq 6$  and. Then Protocol lss inserts the entry  $(\text{id}, xpk = \prod_{i=1}^6 h_i^{x_i}, cert = (A, e))$  into  $UL$  which is considered part of the public param.

**Protocol**  $\text{GSig}(\text{id}, xsk_{\text{id}} = (A, e, x_1, \dots, x_6), M)$ : It outputs signature  $\sigma$  which is a signature proof of knowledge (non-interactive zero-knowledge proof-of-knowledge) of the following proof system

$$\begin{aligned} SPK\{ \{(A, e, x_1, x_2, x_3, x_4, x_5, x_6) : A^{\gamma+e} \prod_{1 \leq i \leq 6} h_i^{x_i} = h_0 \wedge z_1 = x_2 - cx_1 \wedge z_3 = x_4 - cx_3 \\ \wedge z_5 = x_6 - cx_5 \text{ where } c \text{ is the challenge of this proof} \wedge S = \mathbf{g}_{\text{bsn}}^{x_3}\}(\text{param}, \text{nonce}, M) \end{aligned} \quad (7)$$

Further instantiation details of  $\text{GSig}$  are below: The commitments are

$$\begin{aligned} T_A = Ag_A^{s_A}, \quad D_0 = \hat{e}(T_A, u)^{r_e} \hat{e}(g_A, u^\gamma)^{-r_A} \hat{e}(g_A, u)^{-r_0} \prod_{1 \leq i \leq 6} \hat{e}(h_i, u)^{r_{x,i}}, \quad T_1 = g_1^{x_1} g_2^{s_1}, \\ T_2 = g_1^{x_2} g_2^{s_2}, \quad T_3 = g_3^{x_3} g_4^{s_3}, \quad T_4 = g_3^{x_4} g_4^{s_4}, \quad T_5 = g_5^{x_5} g_6^{s_5}, \quad T_6 = g_5^{x_6} g_6^{s_6}, \quad S = \mathbf{g}_{\text{bsn}}^{x_3}, \quad D_s = \mathbf{g}_{\text{bsn}}^{r_{x,3}}, \\ D_1 = g_1^{r_{x,1}} g_2^{r_1}, \quad D_2 = g_1^{r_{x,2}} g_2^{r_2}, \quad D_3 = g_3^{r_{x,3}} g_4^{r_3}, \quad D_4 = g_3^{r_{x,4}} g_4^{r_4}, \quad D_5 = g_5^{r_{x,5}} g_6^{r_5}, \quad D_6 = g_5^{r_{x,6}} g_6^{r_6} \end{aligned}$$

where  $r_{x,1} = x_2, r_{x,3} = x_4, r_{x,5} = x_6, r_1 = s_2, r_3 = s_4, r_5 = s_6$ , and thus  $T_2 = D_1, T_4 = D_3, T_6 = D_5$ . Note  $\hat{e}(h_0, u) \hat{e}(T_A, u^\gamma)^{-1} = \hat{e}(T_A, u)^e \hat{e}(g_A, u^\gamma)^{-s_A} \hat{e}(g_A, u)^{-s_0} \prod_{1 \leq i \leq 6} \hat{e}(h_i, u)^{x_i}$  where  $s_0 = es_A$ . Observe the secrets and randomnesses are mixed, using the technique we call MSR (*Mixed Secrets and Randomnesses*). The challenge is:

$$c = \mathcal{H}(\text{param}, \text{nonce}, M, T_A, T_1, \dots, T_6, S, D_0, \dots, D_6, D_s) \quad (8)$$

The responses are:

$$z_A = r_A - cs_A, \quad z_e = r_e - ce, \quad z_i = r_i - cs_i \text{ for } 0 \leq i \leq 6, \quad z_{x,i} = r_{x,i} - cx_i \text{ for } 1 \leq i \leq 6.$$

The signature is:

$$\sigma = (\text{param}, \text{nonce}, M, T_A, T_1, \dots, T_6, S, c, z_A, z_e, z_0, \dots, z_6, z_{x,1}, \dots, z_{x,6})$$

**Protocol**  $\text{GVf}(\sigma)$  is standard and omitted.

**Protocol**  $\text{Link}(\sigma, \sigma')$ : Verifies the validity of both input signatures. Parses the inputs into  $\sigma = (\dots, S, \dots)$  and  $\sigma' = (\dots, S', \dots)$ . Outputs 1 if  $S = S'$ , and outputs 0 otherwise.

**Protocol**  $\text{Indict}(\sigma, \sigma')$ : Verifies the validity of both input signatures. Parses both signatures. Solves  $x_i, 1 \leq i \leq 6$ , from the two linked signatures. Set  $\text{id} = x_1$ . Retrieve  $xpk_{\text{id}}$  from the user list  $UL$ . Confirm  $xpk_{\text{id}} = \prod_{1 \leq i \leq 6} h_i^{x_i}$ . Output  $\text{id}$ .

The following Theorem analyzes the security of Protocol  $\text{TbL-SDH-PC}$ .

**Theorem 3.** *Protocol  $\text{TbL-SDH-PC}$  is a  $\text{TbL}$  group signature with  $k = 1$  which, assuming the Random Oracle (RO) model,*

1. *is correct;*
2. *is irrevocably anonymous;*
3. *is fully linkable provided the  $q$ -SDH Assumption holds;*
4. *is non-slanderable provided Discrete Logarithm is hard.*

*In summary, Protocol  $\text{TbL-SDH-PC}$  is a secure  $\text{TbL}$  group signature if the  $q$ -SDH Assumption holds and the DDH Assumption in  $G_T$  holds in the RO model.*

*Proof Sketch:* Correctness is straightforward. Noting the user public key  $xpk = \text{PedCom}(x_1, x_2, x_3, x_4, x_5; x_6)$  is a Pedersen commitment [34], our irrevocable anonymity follows from the *perfect statistical hiding* property of Pedersen commitments. Noting our group signature proof system in Equation (7) proves more relations than the group signature proof system of Boneh and Boyen [6], our full linkability follows from a proof similar to [6]'s proof of full traceability. By the same token, our proof of non-slanderability follows a similar path to [6]'s proof of non-frameability.  $\square$

#### 4.5 Another instantiation in pairings: Protocol Tbl-SDH

We construct another Tbl group signature in pairings [31, 42, 6, 7], and reduce its security to a different set of intractability assumptions.

**Init, GKg:** Generate a pairing  $\hat{e} : G_1 \times G_2 \rightarrow G_T$ . Generate all discrete logarithm bases fairly, e.g.  $g_i = \mathcal{H}('g', i) \in G_1$ ,  $\mathbf{g} = \mathcal{H}('g', i) \in G_T$ ,  $h_i = \mathcal{H}('h', i) \in G_1$ ,  $u_i = \mathcal{H}('u', i) \in G_2$ . The group sk-pk pair is  $(\gamma, u^\gamma)$ . Generates a user list  $UL$  which is initially empty. We adopt the flexible notation  $\mathcal{H}$  that it is a full-domain cryptographically secure hash function mapping from a union of mixed domains to a union of mixed ranges. Ambiguity should not arise from the context.

**UKg:** On input  $\text{id}$ , sample the relation  $\mathcal{R}_{user}$  to output  $(usk_{\text{id}}, upk_{\text{id}})$ .

**Protocols Join, lss:** accepts common inputs  $\text{id}$ , Join's additional input  $usk_{\text{id}}$ , lss's additional input  $\gamma$  and proceed as follows:

1. Protocol Join identifies itself as User  $\text{id}$  with knowledge of  $usk_{\text{id}}$ , and then randomly generates  $x'_1, x'_2, x'_3, x'_4$ , with  $x'_1 = \text{id} \cdot x'_2$ . Presents  $h_1^{x'_1}, h_2^{x'_2}, h_3^{x'_3}, h_4^{x'_4}$ ; prove knowledge of their discrete logarithms and that  $x'_1 = \text{id} \cdot x'_2$  holds.
2. Protocol lss verifies the proofs; randomly generates  $x''_1, x''_2, x''_3, x''_4$  satisfying  $x''_1 = \text{id} \cdot x''_2$ ; gives them and a certificate  $(A, e)$  satisfying  $A^{e+\gamma} h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} = h_0 \in G_1$  to Protocol Join, where  $x_i = x'_i + x''_i$ ,  $1 \leq i \leq 4$ . Then Protocol lss inserts the entry  $(\text{id}, xpk = (h_1^{x_1}, h_2^{x_2}, h_3^{x_3}, h_4^{x_4}), cert = (A, e))$  into  $UL$  which is considered part of the public **param**.

**Protocol GSig**( $\text{id}, xsk_{\text{id}} = (A, e, x_1, x_2, x_3, x_4), \text{bsn}, M$ ): It outputs signature  $\sigma$  which is a signature proof of knowledge (non-interactive zero-knowledge proof-of-knowledge) of the following proof system

$$\begin{aligned} SPK\{ \{ (A, e, x_1, x_2, x_3, x_4) : \\ A^{\gamma+e} h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} = h_0 \in G_1 \wedge x_3^{-1} = c x_1^{-1} + z \wedge x_4^{-1} = c x_2^{-1} + z' \\ \wedge c \text{ is the challenge of this proof system} \} (\text{param}, \text{nonce}, \text{bsn}, M) \end{aligned} \quad (9)$$

Further instantiation details of GSig are below: The commitments are

$$\begin{aligned} T_A &= A g_A^{s_A}, \quad [\text{Note } \hat{e}(h_0, u) \hat{e}(T_A, u^\gamma)^{-1} \\ &= \hat{e}(T_A, u)^e \hat{e}(h_1, u)^{x_1} \hat{e}(h_2, u)^{x_2} \hat{e}(h_3, u)^{x_3} \hat{e}(h_4, u)^{x_4} \hat{e}(g_A, u^\gamma)^{-s_A} \hat{e}(g_A, u)^{-s_0} \\ &\quad \text{where } s_0 = e s_A] \quad D_0 = \\ &\hat{e}(T_A, u)^{r_e} \hat{e}(h_1, u)^{r_{x,1}} \hat{e}(h_2, u)^{r_{x,2}} \hat{e}(h_3, u)^{r_{x,3}} \hat{e}(h_4, u)^{r_{x,4}} \hat{e}(g_A, u^\gamma)^{-r_A} \hat{e}(g_A, u)^{-r_0} \\ T_1 &= \mathbf{g}_{\text{bsn},1}^{1/x_1}, \quad T_2 = \mathbf{g}_{\text{bsn},2}^{1/x_2}, \quad [\text{Note } \mathbf{g}_{\text{bsn},1} = T_1^{x_1}, \quad \mathbf{g}_{\text{bsn},2} = T_2^{x_2}] \\ D_1 &= T_3 = T_1^{r_{x,1}}, \quad D_2 = T_4 = T_2^{r_{x,2}}, \quad D_3 = T_1^{r_{x,3}}, \quad D_4 = T_2^{r_{x,4}}, \\ &\quad r_{x,1} = x_3, \quad r_{x,2} = x_4 \end{aligned} \quad (11)$$

Observe the secrets and randomnesses are mixed, using the technique from Section 3. The challenge is:

$$c = \mathcal{H}(\text{param}, \text{nonce}, \text{bsn}, M, T_A, T_1, T_2, D_0, D_1, D_2, D_3, D_4) \quad (12)$$

The responses are:

$$z_A = r_A - c s_A, \quad z_e = r_e - c e, \quad z_0 = r_0 - c s_0, \quad z_{x,i} = r_{x,i} - c x_i, \quad 1 \leq i \leq 4.$$

The signature is:

$$\sigma = (\text{param}, \text{nonce}, \text{bsn}, M, T_A, T_1, T_2, c, z_A, z_e, z_0, z_{x,1}, z_{x,2}, z_{x,3}, z_{x,4})$$

**Protocol GVf**( $\sigma$ ) parses the input, computes

$$\begin{aligned} D_0 &= \hat{e}(T_A, u)^{z_e} \hat{e}(h_1, u)^{z_{x,1}} \hat{e}(h_2, u)^{z_{x,2}} \hat{e}(h_3, u)^{z_{x,3}} \hat{e}(h_4, u)^{z_{x,4}} \\ &\quad \cdot \hat{e}(g_A, u^\gamma)^{-z_A} \hat{e}(g_A, u)^{-z_0} [\hat{e}(h_0, u) \hat{e}(T_A, u^\gamma)^{-1}]^c, \\ D_1 &= T_1^{z_{x,1}} \mathbf{g}_{\text{bsn},1}^c, \quad D_2 = T_2^{z_{x,2}} \mathbf{g}_{\text{bsn},2}^c, \quad D_3 = T_1^{z_{x,3}} D_1^c, \quad D_4 = T_2^{z_{x,4}} D_2^c \end{aligned} \quad (13)$$

Verifies that the challenge  $c$  computed from Equation (12) equals to that parsed from the input in order to output 1.

**Protocol Link**( $\sigma, \sigma'$ ): Verifies the validity of both input signatures. Parses both signatures. Outputs 1 if  $T_1 = T'_1$ , and outputs 0 otherwise.

**Protocol Indict**( $\sigma, \sigma'$ ): Verifies the validity of both input signatures. Parses both signatures. Solves  $x_1^{-1}$  from  $x_3^{-1} = cx_1^{-1} + z_{x,1}$  and  $x_3^{-1} = c'x_1^{-1} + z'_{x,1}$ . Solves  $x_2^{-1}$  similarly. Outputs  $\text{id} = x_1/x_2$ .

The following Theorem analyzes the security of Protocol TbL-SDH.

**Theorem 4.** *Protocol TbL-SDH is a TbL group signature which, assuming the Random Oracle (RO) model,*

1. *is correct;*
2. *is irrevocably anonymous provided the DDH( $G_1, G_T$ ) Assumption and the DDH Assumption in  $G_1$  both hold;*
3. *is fully linkable provided the  $q$ -SDH Assumption holds;*
4. *is non-slanderable provided Discrete Logarithm is hard.*

*In summary, Protocol TbL-SDH is a secure TBL group signature if the DDH( $G_1, G_T$ ) Assumption, the DDH Assumption in  $G_1$ , and the  $q$ -SDH Assumption all hold in the RO model.*

## 5 Discussions, Applications, Conclusions

**Link-and-trace other than identity.** Our TbL group signatures above link-and-trace the signer identity. However, it can be easily modify to link-and-trace the user secret key. In fact, Protocol TbL-SDH (resp. TbL-SRSA) already links-and-traces all four user secret keys  $x_1, x_2, x_3, x_4$ .

**Hybridizing TbL and TbE.** If we also require the TbL group signature to incorporate a verifiable escrow of the signer identity to an OA (Open Authority), then the doubly-signed signatures can be traced by the TbL mechanism and the singly-signed signatures can be traced by the OA. For example, Protocol TbL-SDH becomes

$$\begin{aligned} SPK\{ \{ (A, e, x_1, x_2, x_3, x_4, \rho) : A^{\gamma+e} h_1^{x_1} h_2^{x_2} h_3^{x_3} h_4^{x_4} = h_0 \wedge x_3^{-1} = cx_1^{-1} + z \\ \wedge x_4^{-1} = cx_2^{-1} + z' \wedge c \text{ is the challenge} \wedge \text{ctxt} = \text{Enc}(\text{pk}_{OA}, h_1^{x_1}, \rho) \} (M) \end{aligned}$$

**Sign  $k + 1$  times and be traced.** Our TbL group signature traces after a user signs twice, within the same group and for the same verifier. It can be extended to trace after signing  $k$  times with  $k > 2$  as follows. Option One: Issue each certificate with  $k$  committed randomnesses. Then the certificate can be used  $k$  times within the same group and for the same verifier without revealing the identity. However, signing  $k + 1$  times necessarily uses a certain committed randomness twice and thus results in anonymity revocation. Option Two: Each verifier provides  $k$  sets of discrete-log bases for each group. Then a user with a TbL certificate can sign  $k$  times using the different bases without anonymity revocation. Signing  $k + 1$  times necessarily uses a certain Verifier-specific discrete logarithm bases set twice and thus results in identity extraction.

**Applications** Linkable group (resp. ring) signatures or their equivalents, in the link-but-not-trace paradigm, have been proposed for several applications, including e-cash [27, 15, 37, 29, 28, 39, 38], e-voting [32, 33, 26, 39, 38], DAA (Direct Anonymous Attestation) [13], and anonymous credentials [15]. In each application, an entitled user access its privileges by anonymously authenticate itself with a group (resp. ring) signature or an equivalent mechanism such as anonymous group authentication, anonymous credentials, or DAA. In order to regulate resource use, double or multiple signatures (or *sign-on*'s) by the same user entitlement are linked (but not raced) and countermeasures taken. Typically, a *blacklist* of offenders' *tags* [15, 13] is published to facilitate future detection of linked signatures.

When presented with a signature, the verifier checks its validity, and then confirms it is not on the blacklist before accepting. The blacklist can be available online, or locally cached, or both. Unavoidably, there are synchronization and latency issues with the updating and the availability of the blacklist. An attacker can exploit such vulnerabilities by launching concurrent sign-on sessions with multiple verifiers during network congestion when the blacklist updating and inter-verifier communications are stressed. Then the *offline* verifier

faces a Hobson's choice of either (1) probationally accepts valid signatures (sign-on's) without checking an updated blacklist and suffer the potential damage, or (2) summarily rejects all signatures to err on the safe side.

The TbL paradigm of link-and-trace is an effective deterrent against the above vulnerability exploitation. An offline verifier can probationally accept valid signatures without an updated blacklist. Double signers can be traced and penalized afterwards when the blacklist eventually returns online and is updated. The TbL paradigm does not *prevent* the exploitation, but it is an effective deterrent. Its deterrent effect can also alleviate the urgency of the availability and the updating of the blacklist. We observe that the TbL deterrent is relatively more desirable in a scalable offline anonymous e-cash application when the offline scenario is highly realistic; while it is relatively less significant in an anonymous e-voting scheme where the vote tallying is after the detection of double votes.

**Conclusion** We initiate the formal study of the TbL (Tracing-by-Linking) group signatures. We introduce its security model, and we present the first several instantiations with provable security. Our main construction technique is the mix-the-secrets-and-randomnesses (MSR) technique. It remains interesting to discover alternative mechanisms to achieve TbL other than MSR, to reduce complexity and bandwidth costs, and to construct more flexible instantiations to achieve more versatile features.

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## A A slanderable-but-vindicatable secure TbL group signature

We present an SbV (Slanderable-but-Vindicatable) but otherwise secure TbL group signature scheme. It is an extension of the link-but-not-trace ring signature of [39].

For simplicity we consider a static group model where there is no (Join, lss) within the duration of consideration and there are exactly  $n$  members of the group. The group sk-pk pair is  $(\emptyset, (y_1 = g^{x_1}, \dots, y_n = g^{x_n}))$ . (Yes, there is no group trapdoor.) The sk-pk pair of User  $i$  is  $(x_i, y_i)$ . The TbL group signature is

$$\sigma = SPK\{x : (\bigvee_{1 \leq i \leq n} y_i = g^x) \wedge (\bigvee_{1 \leq i \leq n} \tilde{y}_i = h^x)\}(M) \quad (14)$$

where  $h = \mathcal{H}(\text{nonce})$ , i.e. the hash of a non-repeating value. Note that the signature  $\sigma$  necessarily contains  $\tilde{y}_1, \dots, \tilde{y}_n$ , and therefore it grows in length proportional to the group size  $n$ .

Protocol  $\text{GVF}(\sigma)$  verifies the proof. Assume signatures  $\sigma$  and  $\sigma'$  are both valid and they parse to produce  $\tilde{y}_i$  and  $\tilde{y}'_i$ , respectively. Protocol  $\text{Link}(\sigma, \sigma')$  outputs 1 if and only if  $\tilde{y}_j = \tilde{y}'_j$  for some  $j$ ,  $1 \leq j \leq n$ . And in that case, Protocol  $\text{Indict}(\sigma, \sigma')$  outputs  $j$ .

An attacker other than User  $j$  can produce two valid signatures with the same randomly generated  $\tilde{y}_j$ , and thus indict User  $j$ . But User  $j$  can then vindicate itself by proving the inequality of discrete logarithms:  $\log_g(y_j) \neq \log_h(\tilde{y}_j)$ .  $\square$

## B Tight Reductions among Strong Diffie-Hellman Assumptions

We derive some tight equivalence reductions between several Strong Diffie-Hellman (SDH) assumptions. This Appendix also appeared as [41].

### B.1 Results

Let  $e : G_1 \times G_2 \rightarrow G_T$  be a bilinear mapping. The *k-Strong Diffie-Hellman Problem (k-SDH)* is the problem of computing a pair  $(g_1^{1/(\gamma+x)}, x)$  given  $g_1 \in G_1$ , and  $g_2, g_2^\gamma, g_2^{\gamma^2}, \dots, g_2^{\gamma^k} \in G_2$ . The *k-Strong Diffie-Hellman Assumption* is that no PPT algorithm has a non-negligible probability of solving a random instance of the *k-Strong Diffie Hellman Problem*. For details, see [6, 7].

The *k-SDH Assumption* is closely related to the coalition-resistance of pairing-based signature schemes and group signature schemes [31, 42, 6, 7, 40]. Typically,  $k$  colluders cannot jointly forge an additional signature when the *k-SDH Assumption* holds. The following variants are also related to the coalition-resistance of pairing based signatures and group signatures:

- The *k-SDH' Problem* is the problem of computing a pair  $(g_1^{1/(\gamma+x)}, x)$  given  $g_1, g_1^\gamma, g_1^{\gamma^2}, \dots, g_1^{\gamma^k} \in G_1$  and  $g_2, g_2^\gamma \in G_2$ .
- The *k-CAA Problem* is, given  $g_2, g_2^\gamma \in G_2$ ,  $v \in G_1$ , and and pairs  $(A_i, e_i)$  with distinct and nonzero  $e_i$ 's satisfying  $A_i^{\gamma+e_i} = v$ ,  $1 \leq i \leq k$ , compute a pair  $(A_{k+1}, e_{k+1})$  with  $e_{k+1} \neq e_i$  for any  $i$ ,  $1 \leq i \leq k$ , and satisfying  $A_{k+1}^{\gamma+e_{k+1}} = v$ .
- The *k-CAA2 Problem* is, given  $g_2, g_2^\gamma \in G_2$ ,  $u, v \in G_1$ ,  $(A_i, e_i, x_i)$  satisfying  $A_i^{\gamma+e_i} u^{x_i} = v$  for  $1 \leq i \leq k$  and all  $e_i$ 's are distinct and nonzero, compute another triple  $(A_{k+1}, e_{k+1}, x_{k+1})$  satisfying  $A_{k+1}^{\gamma+e_{k+1}} u^{x_{k+1}} = v$  and  $e_{k+1} \neq e_i$  for any  $i$ ,  $1 \leq i \leq k$ .

The *k-SDH' (resp. k-CAA, k-CAA2) Assumption* is that no PPT algorithm has a non-negligible probability of solving a random instance of the *k-SDH' (resp. k-CAA, k-CAA2) Problem*. The *k-CAA Assumption* is from Zhang, et al.[42], where CAA stands for *Collusion Attack Algorithm*. They showed the *k-CAA Assumption* holds if and only if their group signature scheme is *k-coalition resistant*. [6, 7] showed the *k-CAA Assumption* is at least as strong as the *k-SDH Assumption*. However, no reduction in the opposite direction was given. The *full traceability* of the *exculpable* version of [7]'s group signature in their Section 7 can be easily shown equivalent to the *k-CAA2 Assumption*. [40] showed the *k-CAA2 Assumption* is at least as strong as the *k-SDH Assumption*.

The *k-CAA2 Assumption* is easily at least as strong as the *k-CAA Assumption*. Typically, there exists an efficiently computable homomorphism  $\psi$  such that  $\psi(g_2) = g_1$ . Then the *k-SDH Assumption* is at least as strong as the *k-SDH' Assumption*. In Section B.2, we prove the following two Theorems:

**Theorem 5.** *The k-SDH' Assumption and the k-CAA Assumption are equivalent.*

**Theorem 6.** *Assume the discrete log value  $\log_v(u)$  is known. Then the k-SDH' Assumption and the k-CAA2 Assumption are equivalent.*

In proving results concerning SDH-related protocols,  $u$  is often the output of a fair hashing function. Then the value of  $\log_v(u)$  is known under the random oracle model. In such cases, Theorem 6 can be used to establish equivalence between certain SDH-based signature and group signature schemes and the  $k$ -SDH' Assumption. It remains interesting to explore other equivalence reductions between these and other SDH-related assumptions, and their applications to pairing-based signatures and group signatures.

We also note that the above equivalence reductions are *tight*, meaning that one solution algorithm's time complexity (resp. success probability) is within a reasonable additive term of the solution algorithm of the other problem. Such tightness will be established by our proofs below.

## B.2 Proofs

**B.2.1 Proof Sketch of Theorem 5** (1) *Solving  $k$ -CAA Problem implies solving  $k$ -SDH' Problem.* Assume PPT algorithm  $\mathcal{A}$  solves  $k$ -CAA. Given a  $k$ -SDH' problem instance, randomly generate distinct nonzero  $e_i$ ,  $1 \leq i \leq k$ . Let  $f(\gamma) = \prod_{i=1}^k (\gamma + e_i)$ . Denote  $f(\gamma) = \sum_{i=0}^k f_i \gamma^i$ . Let  $v = g_1^{f(\gamma)}$ . For  $1 \leq i \leq k$  let  $f^{[j]} = f(\gamma)/(\gamma + e_j) = \sum_{i=0}^{k-1} f_i^{[j]} \gamma^i$ . Then

$$A_j = v^{1/(\gamma+e_j)} = g_1^{f^{[j]}(\gamma)} = g_1^{\sum_{i=0}^{k-1} f_i^{[j]} \gamma^i} = \prod_{i=0}^{k-1} (g_1^{\gamma^i})^{f_i^{[j]}}$$

Note that for each  $j$ ,  $1 \leq j \leq k$ , we have  $A_j^{\gamma+e_j} = v$ . Invoking  $\mathcal{A}$  to solve this  $k$ -CAA Problem, we obtain  $(A_{k+1}, e_{k+1})$  satisfying  $A_{k+1}^{\gamma+e_{k+1}} = v$ . Denote  $B = v^{\hat{f}(\gamma)^{-1}}$  where  $\hat{f}(\gamma) = f(\gamma)(\gamma + e_{k+1})$ . Next, we describe how to compute  $B$ . Denote  $\hat{f}(\gamma) = \sum_{i=0}^{k+1} \hat{f}_i \gamma^i$  and

$$\hat{f}^{[j]}(\gamma) = \hat{f}(\gamma)(\gamma + e_j)^{-1} = \prod_{1 \leq i \leq k+1, i \neq j} (\gamma + e_i) = \sum_{i=1}^k \hat{f}_i^{[j]} \gamma^i$$

for  $1 \leq j \leq k+1$ . Denote  $\tilde{e} = e_{k+1}$ , we have

$$\begin{aligned} B^{\gamma^{j+1} + \gamma_j \tilde{e}} &= B^{(\gamma^j + \gamma^{j-1} \tilde{e})\gamma} = g_1^j, \text{ for } 0 \leq j \leq k \\ B^{\hat{f}(\gamma)} &= v \end{aligned}$$

The above system of  $k+2$  equations can be solved for the  $k+2$  unknowns  $B^{\gamma^\ell}$ ,  $0 \leq \ell \leq k+1$ , including  $B$  where  $(B, \tilde{e})$  solves the  $k$ -SDH' Problem.

(2) *Solving  $k$ -SDH' Problem implies solving  $k$ -CAA Problem.* Assume  $\mathcal{A}$  is a PPT solver of the  $k$ -SDH' Problem. Given  $A_i^{\gamma+e_i}$ ,  $1 \leq i \leq k$ , let  $f(\gamma) = \prod_{i=1}^k (\gamma + e_i)$ . Let  $g_1 = v^{1/f(\gamma)}$ . Next, we describe how to compute  $g_1$ .

Denote  $f(\gamma) = \sum_{i=0}^k f_i \gamma^i$  and  $f^{[j]}(\gamma) = f(\gamma)/(\gamma + e_j) = \sum_{i=0}^{k-1} f_i^{[j]} \gamma^i$ , for  $1 \leq j \leq k$ . We have  $v = g_1^{f(\gamma)} = \prod_{i=0}^k (g_1^{\gamma^i})^{f_i}$  and

$$A_j = g_1^{f^{[j]}(\gamma)} = \prod_{i=0}^k (g_1^{\gamma^i})^{f_i^{[j]}} \quad (15)$$

Rearranging, we have

$$\prod_{i=0}^k (g_1^{\gamma^i})^{M_{i,j}} = A_j, \text{ for } 0 \leq j \leq k, \quad (16)$$

where the  $(k+1) \times (k+1)$  matrix  $\bar{\mathbf{M}}$  is

$$\bar{\mathbf{M}} = [M_{i,j}]_{0 \leq i,j \leq k} = \begin{bmatrix} f_0 & f_1 & \cdots & f_k \\ 0 & f_1^{[1]} & \cdots & f_k^{[1]} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & f_1^{[k]} & \cdots & f_k^{[k]} \end{bmatrix}$$



Note  $f_i^{[j]} = S_{k-1-i}(E \setminus \{e_j\})$  for all  $i$  and  $j$ ,  $1 \leq i \leq k-1$ ,  $1 \leq j \leq k$ , where  $E = \{e_1, \dots, e_k\}$  and  $S_a(\{x_1, \dots, x_n\})$  is the  $a$ -th order symmetric function

$$S_a(\{x_1, \dots, x_n\}) = \sum_{1 \leq i_1 < \dots < i_a \leq n} x_{i_1} \cdots x_{i_a}$$

Denote the  $k \times k$  matrix  $\mathbf{M} = [M_{i,j}]_{1 \leq i, j \leq k}$ . We prove the following Lemma later:

**Lemma 7**  $\det(\mathbf{M}) = \prod_{1 \leq i < j \leq k} (e_i - e_j)$ .

Therefore  $\det(\bar{\mathbf{M}}) = (\prod_{\ell=1}^k e_\ell) (\prod_{1 \leq i, j \leq k} (e_i - e_j)) \neq 0$ , and Equation (16) can be solved to obtain  $g_1^{\gamma^i}$ , for all  $i$ ,  $0 \leq i \leq k$ . Invoking the  $k$ -SDH' solver  $\mathcal{A}$  to obtain  $g_1^{1/(\gamma+x)}$  and  $x$ .

Let  $\bar{f}(\gamma) = \sum_{i=0}^{k-1} \bar{f}_i \gamma^i$  and  $\bar{c}$  be such that  $f(\gamma)/(\gamma+x) = \bar{f}(\gamma) + \bar{c}/(\gamma+x)$ . Then compute

$$A_{k+1} = g_1^{f(\gamma)/(\gamma+x)} = g_1^{\bar{f}(\gamma)} (g_1^{1/(\gamma+x)})^{\bar{c}} = \left[ \prod_{i=0}^{k-1} (g_1^{\gamma^i})^{\bar{f}_i} \right] (g_1^{1/(\gamma+x)})^{\bar{c}}$$

and we solve  $k$ -CAA Problem with  $(A_{k+1}, x)$ . □

**B.2.2 Proof of Lemma 7** Note  $\mathbf{M}$  equals the following matrix:

$$\mathbf{M}(k, e_1, \dots, e_k) = \begin{bmatrix} S_{k-1}(E \setminus \{e_1\}) & S_{k-2}(E \setminus \{e_1\}) & \cdots & S_0(E \setminus \{e_1\}) \\ S_{k-1}(E \setminus \{e_2\}) & S_{k-2}(E \setminus \{e_2\}) & \cdots & S_0(E \setminus \{e_2\}) \\ \vdots & \vdots & \ddots & \vdots \\ S_{k-1}(E \setminus \{e_k\}) & S_{k-2}(E \setminus \{e_k\}) & \cdots & S_0(E \setminus \{e_k\}) \end{bmatrix}$$

By convention  $S_0 = 1$ . We prove the the following statement:

$$\det(\mathbf{M}(k, e_1, \dots, e_k)) = \left( \prod_{i=2}^k (e_1 - e_i) \right) \det(\mathbf{M}(k-1, e_2, \dots, e_k)) \quad (17)$$

Then induction on  $k$  yields the Lemma.

Let matrix

$$\mathbf{U} = \begin{bmatrix} 1 & -1 & -1 & \cdots & -1 \\ & 1 & & & \\ & & \ddots & & 0 \\ 0 & & & \ddots & \\ & & & & 1 \end{bmatrix}$$

Multiplying two matrices we obtain  $\mathbf{M}(k, e_1, \dots, e_k) \mathbf{U} =$

$$\begin{bmatrix} S_{k-1}(E \setminus \{e_1\}) & S_{k-2}(E \setminus \{e_1\}) & \cdots & S_1(E \setminus \{e_1\}) & S_0(E \setminus \{e_1\}) \\ (e_1 - e_2) S_{k-2}(E \setminus \{e_1, e_2\}) & (e_1 - e_2) S_{k-3}(E \setminus \{e_1, e_2\}) & \cdots & (e_1 - e_2) S_0(E \setminus \{e_1, e_2\}) & 0 \\ (e_1 - e_3) S_{k-2}(E \setminus \{e_1, e_3\}) & (e_1 - e_3) S_{k-3}(E \setminus \{e_1, e_3\}) & \cdots & (e_1 - e_3) S_0(E \setminus \{e_1, e_3\}) & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ (e_1 - e_k) S_{k-2}(E \setminus \{e_1, e_k\}) & (e_1 - e_k) S_{k-3}(E \setminus \{e_1, e_k\}) & \cdots & (e_1 - e_k) S_0(E \setminus \{e_1, e_k\}) & 0 \end{bmatrix}$$

Consider the lower left  $(k-1) \times (k-1)$  matrix. Its  $i$ -th row is exactly the  $i$ -th row of  $\mathbf{M}(k-1, E \setminus \{e_1\})$  multiplied by  $e_1 - e_i$ . This proves Equation (17) and thus the Lemma. □

**B.2.3 Proof Sketch of Theorem 6** Assume  $\log_v(u) = \alpha$ . The proof is similar to that of Theorem 5. We describe mainly the difference below. Given a PPT algorithm  $\mathcal{A}$  which solves  $k$ -CAA2, and a  $k$ -SDH' Problem instance, randomly generate distinct nonzero  $e_i$  and  $x_i$ ,  $1 \leq i \leq k$ . Let  $f(\gamma)$ ,  $f^{[i]}(\gamma)$  be as defined in the proof of Theorem 5. Then

$$A_j = v^{(1-x_i\alpha)/(\gamma+e_i)} = g_1^{(1-x_i\alpha)f^{[i]}(\gamma)}$$

Invoking  $\mathcal{A}$  to obtain  $(A_{k+1}, e_{k+1}, x_{k+1})$  satisfying  $A_{k+1}^{\gamma+e_{k+1}} u^{x_{k+1}} = v$ . The rest is similar to the proof of Theorem 5.

Given a PPT algorithm  $\mathcal{A}$  which solves the  $k$ -SDH' Problem and a  $k$ -CCA2 Problem instance, we have  $A_i^{\gamma+e_i} = v^{1-x_i\alpha}$ . Let  $g_1 = v^{1/f(\gamma)}$ , then Equation (15) becomes

$$A_j = g_1^{(1-x_i\alpha)f^{[j]}(\gamma)}, 1 \leq j \leq k.$$

The non-singularity of the matrix  $\bar{\mathbf{M}}$  ensures that a  $k$ -SDH' Problem instance can be computed from the  $A_j$ 's. Invoke  $\mathcal{A}$  to solve this problem instance, and then convert its answer to an answer for the  $k$ -CAA2 Problem is straightforward.  $\square$