# Short Code-Based One-out-of-Many Proofs and Applications 

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#### Abstract

In this work, we propose two novel succinct one-out-of-many proofs from coding theory, which can be seen as extensions of the Stern's framework and Veron's framework from proving knowledge of a preimage to proving knowledge of a preimage for one element in a set, respectively. The size of each proof is short and scales better with the size of the public set than the code-based accumulator in [35]. Based on our new constructions, we further present a logarithmic-size ring signature scheme and a logarithmic-size group signature scheme. Our schemes feature short signature sizes, especially our group signature. To our best knowledge, it is the most compact code-based group signature scheme so far. At 128 -bit security level, our group signature size is about 144 KB for a group with $2^{20}$ members while the group signature size of the previously most compact code-based group signature constructed by the above accumulator exceeds 3200 KB .


Keywords: code-based cryptography • one-out-of-many proofs • set-membership proofs • ring signatures • group signatures

## 1 Introduction

Code-based cryptography is the study of cryptosystems based on error-correcting codes that originated from the pioneering work of McEliece [29]. It is able to resist quantum attacks and is widely regarded as an important research branch in post-quantum cryptography. In particular, NIST's recent call for post-quantum standardization has propelled advancements in this area.

Zero-knowledge proofs are a fundamental primitive in cryptography. In 1993, Stern proposed the first code-based zero-knowledge argument of knowledge (ZKA oK) based on the hardness of the syndrome decoding (SD) problem [38]. This proof enables one to demonstrate knowledge of a low-weight preimage for a syndrome. Later, Veron introduced a ZKAoK for the general syndrome decoding (GSD) problem, which is the "dual" problem of the SD problem [39]. Subsequently, several optimization schemes have been proposed within this framework $[5,7,11,31,39]$, as well as applied to other hard problem settings [20,24, 26].

Moreover, variants of the Stern protocol or the Veron protocol have been utilized to construct numerous advanced cryptographic schemes, such as proofs of valid opening for code-based commitment schemes [35], verifiable encryption [34], ring signatures $[9,10,30]$, group signatures $[1,8,17]$ and accumulators $[3,35]$.

An important tool in zero-knowledge proofs is one-out-of-many proofs, which enable one to demonstrate knowledge of an opening to a commitment within a list of commitments. This concept is closely related to some primitives such as setmembership proofs and ring signatures. Groth and Kohlweiss initially provided an efficient one-out-of-many proof based on discrete logarithms and applied it in ring signatures [21]. Subsequently, Esgin et al. constructed a lattice-based one-out-of-many proof [16]. In 2022, Lyubashevsky et al. further constructed a more efficient lattice-based one-out-of-many proof and based on this proof, they proposed a logarithmic ring signature and a logarithmic group signature [28].

However, similar constructions in code-based cryptography are not practical. In 2015, Ezerman et al. proposed a construction for proving knowledge of a secret for one syndrome in a public set, and applied it to build a code-based group signature scheme [17]. The group signature size is linear to the number $N$ of group members. While it has a short signature size with a small $N$, as $N$ grows to $2^{20}$, its signature size increases to 19 MB under the 128 -bit security level. The similar construction can be found in [2,8]. In 2019, Nguyen et al. put forward a code-based Merkle-tree accumulator, which is a logarithmic-size set-membership proof [35]. Based on this building block, the authors constructed logarithmic-size ring signature and group signature schemes. In 2020, Beullers et al. developed a general group-action based ring signature framework [6]. Subsequently, Barenghi et al. and Chou et al. instantiated the group action using the code equivalence problem [4] and the matrix code equivalence problem [13], respectively, and proposed efficient ring signature schemes. However, no group signature scheme has been constructed based on these two problems so far.

### 1.1 Our Contributions

Our main cryptographic results are summarized as follows (we describe them in more detail in our technique overview):

- We propose a novel short code-based one-out-of-many proof. Our construction can be seen as an extension of Stern's framework from proving knowledge of a preimage to proving knowledge of a preimage for one element in a public set. The main advantage of our framework is that the growth rate of the proof size relative to the public set size $N$ is very low even compared to the codebased accumulator (Asiacrypt 2019). This is because the term related to $N$ in the expression of the signature size of our schemes is simply determined by the path of a $\log N$-deep Merkle tree, that is $2 \lambda \log N$, where $\lambda$ is the security level, and so is independent of the parameters of the hard problem. The codebased accumulator achieves membership proof by proving knowledge of a hash chain that is linearly related to the parameters of the regular SD problem. This makes the coefficient of $\log N$ much larger than ours.
- To further reduce the proof size, we propose a more efficient GSD-based one-out-of-many proof based on Veron's framework and optimization techniques proposed in [23,31]. Then, we apply this one-out-of-many proof to the construction of a logarithm-size ring signature. Next, we compare our ring signature with other code-based ring signatures in Table 1.
- We construct a new set membership proof by transforming the framework of building one-out-of-many proofs into the framework of building set membership proofs. This transformation is similar to the ideas in [21]. Moreover, this set membership proof serves as a building block in our group signature.
- Combining our GSD-based one-out-of-many proof and the set-membership proof, we present a logarithm-size group signature, which is the most compact code-based group signature scheme to date. We also make the comparison with other code-based group signatures in Table 2. For convenience, we use the parameter sets for SD problem in [18], and the parameter sets for the McEliece encryption scheme in [12]. The above comparison indicates that the signature sizes of both our ring signature and group signature schemes are significantly shorter than previous schemes except the BBNPS in [4], whose security relies on the code equivalence problem.

Table 1. Comparison of ring signature size (KB) under the 128-bit security level.

|  | $N$ |  |  | asymptotic sig.size | hardness assumption |
| :--- | ---: | ---: | ---: | :--- | :--- |
|  | $2^{8}$ | $2^{12}$ | $2^{20}$ |  |  |
| ELLNW [17] | 55 | 124 | 19273 | $\mathcal{O}(N)$ | SD |
| BGM [8] | 134 | 205 | 19354 | $\mathcal{O}(N)$ | rank SD |
| NTWZ [35] | 1189 | 1741 | 2847 | $\mathcal{O}(\log N)$ | regular SD |
| BBNPS [4] | 16 | 20 | 28 | $\mathcal{O}(\log N)$ | code equivalence |
| Our work | 55 | 65 | 83 | $\mathcal{O}(\log N)$ | GSD |

Table 2. Comparison of group signature size (KB) under the 128-bit security level.

|  | N |  |  | asymptotic sig.size |  |
| :--- | ---: | ---: | ---: | :--- | :--- | Anonymity

### 1.2 Technical Overview

SD-Based One-out-of-Many Proofs. Our novel SD-based one-out-of-many proof is an extension to Stern's framework. To construct the protocol, we begin
by making a modification to the original Stern protocol. Let $\mathbf{H} \in \mathbb{F}_{2}^{(n-k) \times n}$ and $\mathbf{s} \in \mathbb{F}_{2}^{n-k}$ denote a matrix and a syndrome, respectively. To prove the possession of a small-weight vector $\mathbf{e} \in \mathbb{F}_{2}^{n}$ such that $\mathbf{H e}{ }^{\top}=\mathbf{s}^{\top}$, a prover samples a random vector $\mathbf{r} \in \mathbb{F}_{2}^{n}$ and a random permutation $\phi$, and then sends commitments $c_{1}=$ $\operatorname{Com}\left(\phi, \mathbf{H r}^{\top}+\mathbf{s}^{\top} ; \rho_{1}\right), c_{2}=\operatorname{Com}\left(\phi(\mathbf{r}) ; \rho_{2}\right)$ and $c_{3}=\operatorname{Com}\left(\phi(\mathbf{r}+\mathbf{e}) ; \rho_{3}\right)$ to a verifier. If the challenge $c h$ is 1 , the prover opens $c_{2}$ and $c_{3}$. If $c h=2$, it opens $c_{1}$ and $c_{3}$. If $c h=3$, it opens $c_{1}$ and $c_{2}$. The modified Stern protocol is depicted in Fig. 1. The only difference between our protocol in Fig. 1 and the original Stern protocol is that in the former $c_{1}=\operatorname{Com}\left(\phi, \mathbf{H r}^{\top}+\mathbf{s}^{\top} ; \rho_{1}\right)$ while in the latter $c_{1}=$ $\operatorname{Com}\left(\phi, \mathbf{H r}^{\top} ; \rho_{1}\right)$. Clearly, this modification does not affect the completeness, soundness, and zero-knowledge property of the modified protocol.

Observe two key facts: (1) The modified protocol's $c_{1}$ is related to the public key $\mathbf{s}$, while $c_{2}$ and $c_{3}$ are not related to $s$. (2) During the verification phase, only when $c h=3$, the verifier needs to use the public key $\mathbf{s}$ to check the value of $c_{1}$. These two observations inspire us to construct a one-out-of-many proof based on our modified protocol.

For a statement composing of a matrix $\mathbf{H}$ and $N$ syndromes $\left(\mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right)$, a prover claims that it knows the small-weight preimage $\mathbf{e}$ of one of the syndromes satisfying $\mathbf{H e}^{\top}=\mathbf{s}_{I}^{\top}$ for some $I \in[N],[N]:=\{1, \cdots, N\}$. To demonstrate this, the prover begins by sampling a random mask vector $\mathbf{r}$, a random permutation $\phi$ and $N$ random coins $\left\{b_{i}\right\}_{i=1}^{N}$ to simulate $c_{1}^{i}=\operatorname{Com}\left(\phi, \mathbf{H e}^{\top}+\mathbf{s}_{i}^{\top} ; b_{i}\right)$ for all $i \in[N]$. Subsequently, it samples two random coins $\rho_{2}$ and $\rho_{3}$ to generate $c_{2}=\operatorname{Com}\left(\phi(\mathbf{r}) ; \rho_{2}\right)$ and $c_{3}=\operatorname{Com}\left(\phi(\mathbf{r}+\mathbf{e}) ; \rho_{3}\right)$. The prover then permutes $\left(c_{1}^{1}, \cdots, c_{1}^{N}\right)$ in random order and sends them along with $c_{2}$ and $c_{3}$ to a verifier. If the verifier returns 1 , the prover will open $c_{2}$ and $c_{3}$ by revealing $\left(\phi(\mathbf{r}), \phi(\mathbf{r}+\mathbf{e}), \rho_{2}, \rho_{3}\right)$. This does not leak any information about the witness $\mathbf{e}$ and the index $I$. If the verifier returns 2 , the prover will open $c_{1}^{I}$ and $c_{3}$ by revealing $\left(\phi, \mathbf{r}+\mathbf{e}, \rho_{1}, b_{I}, \rho_{3}\right)$. Since the verifier receives a random permutation of $\left(c_{1}^{1}, \cdots, c_{1}^{N}\right)$ and only verifies whether $c_{1}^{I}$ is in it, this also does not leak any information about the index $I$ and witness $\mathbf{e}$. If the verifier returns 3, the prover will open all $\left\{c_{1}^{i}\right\}_{i=1}^{N}$ and $c_{2}$ by outputting $\phi, \mathbf{r}$ and all random coins $\left\{b_{i}\right\}_{i=1}^{N}$. Therefore, no information about the witness e and the index $I$ is leaked.

In the above process, the prover sends $N+2$ commitments $\left(\left\{c_{1}^{i}\right\}_{i=1}^{N}, c_{2}, c_{3}\right)$ during the commitment phase. In the response phase, when the received challenge is 3 , the prover needs to open these $N+2$ commitments by outputting $N+2$ random coins. Therefore, the proof size grows linearly with $N$. To reduce the proof size, we use a seedtree to generate $N$ random coins required for these $N$ commitments $\left\{c_{1}^{i}\right\}_{i=1}^{N}$, and compress these commitments into a root using a Merkle tree. Specifically, the prover first samples a random seed, and then uses a pseudo-random number generator (PRNG) to iteratively generate $N$ random coins required for the $N$ commitments $\left\{c_{1}^{i}\right\}_{i=1}^{N}$. Subsequently, the prover arranges these $N$ commitments in lexicographical order and compresses the sorted list into a root using a Merkle tree. This trick is inspired by [6]. Next, the prover sends (root, $c_{2}, c_{3}$ ) to the verifier. If the verifier returns 1 , the prover's output remains unchanged. If the verifier returns 2 , the prover opens $c_{I}$ and $c_{3}$ by outputting

Round 1: $\mathcal{P}((\mathbf{H}, \mathbf{s}), \mathbf{e})$ chooses the following random objects:

$$
\mathbf{r} \stackrel{\&}{\leftarrow} \mathbb{F}_{2}^{n}, \phi \stackrel{\perp}{\leftarrow} \mathcal{S}_{n}, \rho_{1}, \rho_{2}, \rho_{3} \stackrel{\&}{\leftarrow}\{0,1\}^{\lambda} .
$$

and sends CMT $:=\left(c_{1}, c_{2}, c_{3}\right)$ to $\mathcal{V}$, where

$$
c_{1}=\operatorname{Com}\left(\phi, \mathbf{H r}^{\top}+\mathbf{s}^{\top} ; \rho_{1}\right), c_{2}=\operatorname{Com}\left(\phi(\mathbf{r}) ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\phi(\mathbf{r}+\mathbf{e}) ; \rho_{3}\right) .
$$

Round 2: $\mathcal{V}$ (CMT) sends a $\operatorname{ch} \leftarrow\{1,2,3\}$ to $\mathcal{P}$.
Round 3: $\mathcal{P}((\mathbf{H}, \mathbf{s}), \mathrm{e}, c h)$ :

- $c h=1$ : Set $\mathbf{v}_{1}=\phi(\mathbf{r}), \mathbf{v}_{2}=\phi(\mathbf{e})$ and send RSP $=\left(\mathbf{v}_{1}, \mathbf{v}_{2}, \rho_{2}, \rho_{3}\right)$ to $\mathcal{V}$.
$-c h=2$ : Set $\mathbf{u}_{1}=\mathbf{r}+\mathbf{e}, \pi_{1}=\phi$ and send $\operatorname{RSP}=\left(\mathbf{u}_{1}, \pi_{1}, \rho_{1}, \rho_{3}\right)$ to $\mathcal{V}$.
- ch $=3$ : Set $\mathbf{u}_{2}=\mathbf{r}, \pi_{2}=\phi$ and send $\operatorname{RSP}=\left(\mathbf{u}_{2}, \pi_{2}, \rho_{1}, \rho_{2}\right)$ to $\mathcal{V}$.

Verification: $\mathcal{V}$ (CMT, ch, RSP):

- ch = 1: Check if $c_{2}=\operatorname{Com}\left(\mathbf{v}_{1} ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\mathbf{v}_{1}+\mathbf{v}_{2} ; \rho_{3}\right)$ and $\mathbf{v}_{2} \in B(n, t)$.
- ch $=2$ : Check if $c_{1}=\operatorname{Com}\left(\pi_{1}, \mathbf{H} \mathbf{u}_{1}^{\top} ; \rho_{1}\right)$ and $c_{3}=\operatorname{Com}\left(\pi_{1}\left(\mathbf{u}_{1}\right) ; \rho_{3}\right)$.
- ch $=3$ : Check if $c_{1}=\operatorname{Com}\left(\pi_{2}, \mathbf{H u}_{2}^{\top}+\mathbf{s}^{\top} ; \rho_{1}\right)$ and $c_{2}=\operatorname{Com}\left(\pi_{2}\left(\mathbf{u}_{2}\right) ; \rho_{2}\right)$.

Fig. 1. The modified Stern protocol. Let $B(n, t)$ denote the set of vectors $\mathbf{v} \in \mathbb{F}_{2}^{n}$ such that its Hamming weight $w(\mathbf{v})=t, \mathcal{S}_{n}$ denote the symmetric group of all permutations of $n$ elements and Com denote a commitment scheme with the binding and hiding property.
$\left(\phi, \mathbf{r}+\mathbf{e}, \rho_{1}, b_{I}, \rho_{3}\right)$ and the path of $c_{I}$ in the Merkle tree. So the length of the path is $\log N$. If the verifier returns 3 , the verifier opens all $\left\{c_{1}^{i}\right\}_{i=1}^{N}$ and $c_{2}$ by outputting ( $\phi, \mathbf{r}$ ) and seed.

GSD-Based One-out-of-Many Proofs. In 1997, Veron pointed that the GSD-based protocol with a ternary challenge space has lower communication cost than the Stern protocol [39]. The GSD problem is to find two vectors $\mathbf{x} \in \mathbb{F}_{2}^{k}$ and $\mathbf{e} \in B(n, t)$ such that $\mathbf{y}=\mathbf{x} \mathbf{G}+\mathbf{e}$ given a matrix $\mathbf{G} \in \mathbb{F}_{2}^{k \times n}$ and a vector $\mathbf{y} \in \mathbb{F}_{2}^{n}$. Although the security proof of this construction [39] has been pointed out to have an issue [22], it has been fixed by Gaborit et al. [5]. The fixed protocol still maintains low communication cost. This improvement is due to the use of the GSD problem instead of the SD problem. In fact, the hardness of two problems is equivalent, while the only difference lies in the use of a generator matrix in the former and a parity-check matrix in the latter. Inspired by this, we construct a GSD-based one-out-of-many proof. Additionally, we use three techniques, namely small-weight vector compression functions [31], seedtrees and Merkle trees [23] to reduce the communication cost of multi-iteration protocols. Seedtrees are used to generate random objects required while Merkle trees are employed to compress commitments in multi-iteration protocols.

Our GSD-based one-out-of-many proof naturally lead to a ring signature scheme by the Fiat-Shamir transform [19]. Specifically, each user $i$ has a publicprivate key pair $\left(\mathbf{y}_{i},\left(\mathbf{x}_{i}, \mathbf{e}_{i}\right)\right)$, where $\mathbf{y}_{i}=\mathbf{x}_{i} \mathbf{G}+\mathbf{e}_{i}$. The signature of user $i$ for a message $\mu$ is a zero-knowledge proof using our GSD-based one-out-of-many proof for the pair ( $\mathbf{x}_{i}, \mathbf{e}_{i}$ ) satisfying the above equation, where $\mu$ is the input in the random oracle in the Fiat-Shamir heuristic.

Set-Membership Proofs. First we briefly introduce the code-based commitment scheme [33]. For a message $\mathbf{m} \in\{0,1\}^{k_{2}}$, one initially chooses two random vectors $\mathbf{v} \in \mathbb{F}_{2}^{k_{1}}, \mathbf{e} \in B(n, t)$, and obtains a McEliece-type commitment

$$
\operatorname{Com}_{\mathrm{McE}}(\mathbf{m} ;(\mathbf{v}, \mathbf{e}))=(\mathbf{v} \| \mathbf{m}) \mathbf{G}+\mathbf{e}
$$

where $\mathbf{G}=\binom{\mathbf{G}_{1}}{\mathbf{G}_{2}} \in \mathbb{F}_{2}^{k \times n}$ is randomly generated, $\mathbf{G}_{1} \in \mathbb{F}_{2}^{k_{1} \times n}, \mathbf{G}_{2} \in \mathbb{F}_{2}^{k_{2} \times n}, k=$ $k_{1}+k_{2}$. To open a commitment $\mathbf{c}$, one reveals $\mathbf{m}, \mathbf{v}, \mathbf{e}$ and a receiver verifies if $\mathbf{c}=(\mathbf{v} \| \mathbf{m}) \mathbf{G}+\mathbf{e}$.

In our set-membership proof, the public information includes a public set $\mathcal{I}=$ $\left\{\alpha_{1}, \cdots, \alpha_{N}\right\}$ and a commitment $\mathbf{c}$ for some $\alpha_{i}$. A prover's goal is to demonstrate that $\mathbf{c}$ is a commitment to an element in the set $\mathcal{I}$. To achieve this, the prover first generates $\left[\mathbf{c}_{1}=\mathbf{c}+\operatorname{Com}_{\mathrm{McE}}\left(\alpha_{1},(\mathbf{0}, \mathbf{0})\right), \cdots, \mathbf{c}_{N}=\mathbf{c}+\operatorname{Com}_{\mathrm{McE}}\left(\alpha_{N},(\mathbf{0}, \mathbf{0})\right)\right]$, and then proves that one of $\left(\left\{\mathbf{c}_{i}\right\}_{i=1}^{N}\right)$ is a commitment to $\mathbf{0}$. This is equivalent to proving that a prover knows a certain $\mathbf{c}_{i}$ having the form of $\mathbf{v} \mathbf{G}_{1}+\mathbf{e}$, where $\mathbf{e} \in B(n, t)$ and $i \in[N]$.

Group Signatures. We use the enc-then-prove framework to construct our group signature scheme. This framework typically requires three cryptographic layers: a secure signature scheme, a semantically secure encryption scheme and a zero-knowledge protocol connecting the first two layers. Let's now explain the construction of the three components used in our group signature scheme.

Consider a group of size $N$, with each user being denoted by an integer $i \in[N]$. For each $i$, the public key of the User $i$ is $\left(\mathbf{G}, \mathbf{y}_{i}=\mathbf{x}_{i} \mathbf{G}+\mathbf{e}_{i}\right) \in \mathbb{F}_{2}^{k \times n} \times \mathbb{F}_{2}^{n}$, and the private key is $\left(\mathbf{x}_{i}, \mathbf{e}_{i}\right) \in \mathbb{F}_{2}^{k} \times B(n, t)$.

The Signature Layer. The construction in this layer is similar to our ring signature. User $i$ uses our GSD-based one-out-of-many proof to prove that it has a pair $\left(\mathbf{x}_{i}, \mathbf{e}_{i}\right) \in \mathbb{F}_{2}^{k} \times B(n, t)$ satisfying $\mathbf{x}_{i} \mathbf{G}+\mathbf{e}_{i}=\mathbf{y}_{i}$.
The Encryption Layer. To achieve the traceability of group signatures, User $i$ encrypts its index $i$ using the randomized McEliece encryption scheme [36] as follows:

$$
\mathbf{c t}=\operatorname{Enc}_{\mathrm{McE}}(\operatorname{bin}(i),(\mathbf{z}, \mathbf{s}))=(\mathbf{z} \| \operatorname{bin}(i)) \mathbf{G}_{\mathrm{McE}}+\mathbf{s},
$$

where $\mathbf{G}_{\mathrm{McE}} \in \mathbb{F}_{2}^{\ell \times m}$ is the public key of McEliece encryption scheme, $\operatorname{bin}(i)$ is the binary representation of $i$ with length $\ell_{2}, \mathbf{z} \in \mathbb{F}_{2}^{\ell_{1}}, \ell=\ell_{1}+\ell_{2}$ and $\mathbf{s} \in B(m, w)$. Then, User $i$ needs to prove that ct is an encryption to an index in the set $\{1, \cdots, N\}$. This is similar to our set-membership proof. Specifically, User $i$ first generates the set

$$
\left[\mathbf{c t}_{1}=\mathbf{c t}+\operatorname{Enc}_{\mathrm{McE}}(1,(\mathbf{0}, \mathbf{0})), \cdots, \mathbf{c t}_{N}+\operatorname{Enc}_{\mathrm{McE}}(N,(\mathbf{0}, \mathbf{0}))\right],
$$

and proves that $\mathbf{c t}_{i}$ is the encryption of 0 , which means that $\mathbf{c t}_{i}$ has the form of $(\mathbf{z} \| 0) \mathbf{G}_{\mathrm{McE}}+\mathbf{s}$, where $\mathbf{z} \in \mathbb{F}_{2}^{\ell_{1}}$ and $\mathbf{s} \in B(m, w)$.
The Third Layer. User $i$ must prove that it encrypts its own index $i$ honestly, which requires combining the former one-out-of-many proof with the latter setmemberships proof. The overarching concept is to pair the $N+2$ commitments
from the former proof with the $N+2$ commitments from the latter proof respectively, forming $N+2$ pairs sequentially from 1 to $N+2$. Then shuffle the last $N$ commitment pairs related to $\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}$ and $\left\{\mathbf{c t}_{i}\right\}_{i=1}^{N}$, and send them along with another two pairs to a verifier. The remaining steps are similar to our GSD-based one-out-of-many proof, with the difference being what needs to be revealed and verified is the commitment pair.

Finally, we obtain a logarithmic-size group signature through the Fiat-Shamir transform, and we also prove its correctness, traceability, and CPA-anonymity.

### 1.3 Roadmap

The rest of the article is organized as follows. Section 2 provides some required preliminaries for our study. In Sect. 3, we present our novel SD-based and GSDbased one-out-of-many protocols. Our logarithmic-size ring signature scheme and its security proof is provided in Sect.4. In Sect. 5, we give our logarithmicsize group signature scheme. Finally, we choose our parameter sets for our ring signature scheme and group signature scheme in Sect. 6.

## 2 Preliminaries

### 2.1 Hard Problems

For integers $a, b$ and $a \leq b$, the notation $[a ; b]$ denotes the set $\{a, \cdots, b\}$. If $a=1$, then it simplifies to $[b]$. Bold lowercase and uppercase letters denote row vectors and matrices respectively. The transpose of a vector $\mathbf{x}$ is represented by $\mathbf{x}^{\top}$. Let $B(n, t)$ be a set of vectors $\mathbf{v} \in \mathbb{F}_{2}^{n}$ such that the Hamming weight $w(\mathbf{v})=t$. For a set $X, x \stackrel{\$}{\leftarrow} X$ means that $x$ is sampled from $X$ randomly and $\mathbf{x} \stackrel{\Phi, \zeta}{\leftrightarrows} X$ denotes $\mathbf{x}$ is sampled from $X$ using the seed $\zeta$. Let $\mathcal{O}(\cdot)$ denote a random oracle and $\mathcal{A}^{\mathcal{O}(\cdot)}$ denote that an algorithm $\mathcal{A}$ has access to $\mathcal{O}(\cdot)$.

Problem 1 (SD Problem). On input a matrix $\mathbf{H} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{(n-k) \times n}$ and a syndrome $\mathbf{s} \in \mathbb{F}_{2}^{n-k}$, the syndrome decoding problem $\operatorname{SD}(n, k, t)$ asks to find a vector $\mathbf{e} \in \mathbb{F}_{2}^{n}$ such that $\mathbf{s}^{\top}=\mathbf{H e}^{\top}$ and $\mathbf{e} \stackrel{\$}{\stackrel{\&}{\leftarrow}} B(n, t)$.

We only present search version of SD problem. In [32], a reduction from the search version to the decision version is provided. Its dual problem is as follows.

Problem $2\left(G S D\right.$ Problem). On input a matrix $\mathbf{G} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k \times n}$ and a vector $\mathbf{y} \in \mathbb{F}_{2}^{n}$, the general syndrome decoding problem $\operatorname{GSD}(n, k, t)$ asks to find a vector $\mathbf{x} \in \mathbb{F}_{2}^{k}$ and a vector $\mathbf{e} \in \mathbb{F}_{2}^{n}$ such that $\mathbf{y}=\mathbf{x G}+\mathbf{e}, \mathbf{x} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k}$ and $\mathbf{e} \stackrel{\$}{\leftarrow} B(n, t)$.

The hardness of the GSD problem is equivalent to that of the SD problem [39].
Problem 3 (DOOM Problem). On input a matrix $\mathbf{H} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k \times n}$ and a set of $N$ syndromes $\left\{\mathbf{s}_{i}\right\}_{i=1}^{N}$, the decoding one-out-of-many problem $\operatorname{DOOM}(n, k, t, N)$ asks to find a vector $\mathbf{e}_{i} \in \mathbb{F}_{2}^{n}$ for some $i \in[N]$ such that $\mathbf{s}_{i}^{\top}=\mathbf{H e}_{i}^{\top}$ and $\mathbf{e}_{i} \stackrel{\&}{\stackrel{\&}{\leftarrow} B(n, t) .}$

As [37] stated, a variant of information set decoding algorithms can be adapted to the $\operatorname{DOOM}(n, k, t, N)$ problem, resulting in a speedup factor of approximately $\sqrt{N}$. We give the dual version of the DOOM problem.

Problem 4 (GDOOM Problem). On input a matrix $\mathbf{G} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k \times n}$ and a set of $N$ vectors $\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}$, the general decoding one-out-of-many problem $\operatorname{GDOOM}(n$, $k, t, N)$ asks to find a vector $\mathbf{x}_{i} \in \mathbb{F}_{2}^{k}$ and a vector $\mathbf{e}_{i} \in \mathbb{F}_{2}^{n}$ for some $i \in[N]$ such that $\mathbf{y}_{i}=\mathbf{x}_{i} \mathbf{G}+\mathbf{e}_{i}, \mathbf{x}_{i} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k}$ and $\mathbf{e}_{i} \stackrel{\Phi}{\leftrightarrows} B(n, t)$.

### 2.2 Merkle Trees

A Merkle tree is a binary tree that compresses a list of data into a value. It is constructed layer by layer from bottom to top using a collision-resistant hash function. Each node in each layer is a hash value of the concatenation of its associated child nodes. In [6] a special type of Merkle trees called index-hiding Merkle trees was introduced. This tree has the characteristic of sorting the leaf nodes in lexicographical order, rather than based on their indices. Let $\mathcal{H}:\{0,1\}^{*} \rightarrow\{0,1\}^{2 \lambda}$ denote a collision-resistant hash function, and $D=\left(d_{0}, \cdots, d_{2^{\ell}-1}\right)$ denote a data list. A Merkle tree includes the following algorithms.

1. $\operatorname{Mtree}(D) \rightarrow$ (root, tree): With a data list $D$ as input, set $M_{\ell, j}=\mathcal{H}\left(d_{j}\right)$ for $j \in\left[0,2^{\ell}-1\right]$, and iteratively calculate

$$
M_{i, j}=\mathcal{H}\left(M_{i+1,2 j-1}, M_{i+1,2 j}\right), i \in[0, \ell-1], j \in\left[0,2^{i}-1\right] .
$$

Output $M_{0,0}$ as the root.
2. IH-Mtree $(D) \rightarrow$ (root, tree): With a data list $D$ as input, set $M_{\ell, j}=\mathcal{H}\left(d_{j}\right)$ for $j \in\left[0,2^{\ell}-1\right]$, and iteratively calculate

$$
M_{i, j}=\mathcal{H}\left(\left(M_{i+1,2 j-1}, M_{i+1,2 j}\right)_{l e x}\right), i \in[0, \ell-1], j \in\left[0,2^{i}-1\right] .
$$

Output $M_{0,0}$ as the root.
3. Gpath $(\operatorname{tree}, B) \rightarrow$ path: With the structure of a tree and a subset $B$ of $D$ as input, output a list of intermediate nodes that cover all $D \backslash B$. Here, one says that a node set $U$ covers a leaf set $L$ if the union of the leaves in a subtree rooted at each node $u \in U$ is exactly the set $L$.
4. Rebuild $($ path,$B) \rightarrow$ root' $^{\prime}$ With a subset $B$ and a path as input, output a rebuilt root' ${ }^{\prime}$.

There are two important properties about Merkle trees: the binding property and the index-hiding property of the index-hiding Merkle trees. The binding property means that for any subset $S$ that does not belong to the set $D$, finding a path such that $\operatorname{Rebuild}(S$, path $)=\operatorname{Mtree}(D)$ is the same as discovering a collision in $\mathcal{H}$. The index-hiding property means that for any subset $B$ belonging to the set $D$, the path of index-hiding Merkle trees will not reveal any information about the set $B$.

Lemma 1. [6] For a Merkle tree generated by a data list $D$, there exists an algorithm $\mathcal{F}$ that uses the tree and a pair (S, path) satisfying $S \not \subset D$ and Rebuild $(S$, path $)=$ root to generate a collision in $\mathcal{H}$.
Lemma 2. [6] Given an integer $N=2^{\ell}$ and two distributions $\mathcal{X}_{1}$ and $\mathcal{X}_{2}$ over $\{0,1\}^{*}$, the distribution $\mathcal{L}_{I}$, for any $I \in[N]$, is defined as

$$
\mathcal{L}_{I}=\left[\begin{array}{c|c}
d_{I} \stackrel{\$}{\leftarrow} \mathcal{X}_{1}, \\
\left(a_{I}, \text { path, root }\right) & \begin{array}{c}
d_{i} \stackrel{\$}{\leftarrow} \mathcal{X}_{2}, \forall 1 \leq i \leq N, i \neq I, \\
\text { (tree, root) }) \leftarrow \operatorname{IH-Mtree}(D), \\
\text { path } \leftarrow \operatorname{Gpath}(\operatorname{tree}, I) .
\end{array}
\end{array}\right],
$$

where $D=\left(d_{1}, \cdots, d_{N}\right)$. Then $\mathcal{L}_{I}=\mathcal{L}_{J}$ for $\forall I, J \in[N]$.

### 2.3 Seedtrees

A seedtree is also a completely balanced binary tree, but its construction differs from that of a Merkle tree. In this case, a sender starts by selecting a seed as the root of a tree. Then, a pseudo-random number generator is used to create intermediate nodes from top to bottom. By sending some intermediate nodes, the sender reveals specific leaf nodes without disclosing any information about the remaining leaves. Let PRNG : $\{0,1\}^{\lambda} \rightarrow\{0,1\}^{2 \lambda}$ represent a pseudo-random number generator. A seedtree includes the following algorithms.

1. Stree(root, $N) \rightarrow\left(l_{0}, \cdots, l_{2^{\ell}-1}\right):$ With a seed root and an integer $N$ as input, set $M_{0,0}=$ root and iteratively compute

$$
\left(M_{i+1,2 j-1}, M_{i+1,2 j}\right)=\operatorname{PRNG}\left(M_{i, j}\right), i \in[0, \ell-1], j \in\left[0,2^{i}-1\right] .
$$

Define $\left(M_{\ell, 0}, \cdots, M_{\ell, 2^{\ell}-1}\right)$ as leaf nodes $\left(l_{0}, \cdots, l_{2^{\ell}-1}\right)$ and then output them.
2. Oseeds(root, ch) $\rightarrow$ seed $_{\text {inter }}$ : With a root and a challenge ch as input, return a set seed ${ }_{\text {inter }}$ that covers all the leaves with index $i$ such that $c h_{i}=1$.
3. Recover $\left(\operatorname{seed}_{\text {inter }}, \mathbf{c h}\right) \rightarrow\left\{l_{i}\right\}_{i, \text { s.t.ch } h_{i}=1}$ : With a set seed ${ }_{\text {inter }}$ and a challenge ch as input, return all leaf nodes rooted at the nodes in seed ${ }_{\text {inter }}$.
4. Simseeds $(\mathbf{c h}) \rightarrow$ seed $_{\text {inter }}$ : With a challenge $\mathbf{c h}$ as input, return a set seed ${ }_{i n t e r}$ via random sampling, enabling seed ${ }_{\text {inter }}$ to cover all leaves with index $i$ satisfying $c h_{i}=0$.

Lemma 3. [6] Given an integer $N$ and a challenge $\mathbf{c h}$, the distributions $\mathcal{X}_{1}$ and $\mathcal{X}_{2}$ are defined by

$$
\begin{aligned}
& \mathcal{X}_{1}=\left[\begin{array}{c|c}
\text { seed }_{\text {inter }},\left\{\text { leaf }_{i}\right\}_{c h_{i}=0} & \begin{array}{c}
\text { seed } \leftarrow\{0,1\}^{\lambda}, \\
\text { Sleaf } \left._{i}\right\}_{i=1}^{N} \leftarrow \operatorname{Stree}(\text { root }, N), \\
\text { seed }_{\text {inter }} \leftarrow \text { Oseeds }\left(\text { seed }_{\text {root }}, \text { ch }\right) .
\end{array}
\end{array}\right] \text { and } \\
& \mathcal{X}_{2}=\left[\begin{array}{l|c}
\text { seed }_{\text {inter }},\left\{\operatorname{leaf}_{i}\right\}_{c h_{i}=0} & \left\{\text { leaf }_{i}\right\}_{c h_{i}=0} \leftarrow\{0,1\}^{\lambda}, \\
\text { seed }_{\text {inter }} \leftarrow \operatorname{Simseeds}(\mathbf{c h}) .
\end{array}\right] .
\end{aligned}
$$

For any adversary who queries an oracle $\mathcal{Q}$ times, the advantage of distinguishing the two distributions $\mathcal{X}_{1}$ and $\mathcal{X}_{2}$ is at most $\mathcal{Q} / 2^{\lambda}$.

## 3 Short One-out-of-Many Proofs from Coding Theory

We first propose an SD-based one-out-of-many proof along with the security proof. To achieve a lower communication cost, we introduce a GSD-based one-out-of-many proof, in which we decrease the communication cost by employing optimization techniques [23,31].

### 3.1 The SD-Based One-out-of-Many Proof

In this subsection, we put forward our SD-based one-out-of-many proof in Fig. 2 for proving knowledge of the preimage for one syndrome in a public set $\left(\mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right)$. More specifically, the proof is a ZKAoK for the following relation:

$$
\begin{equation*}
R=\left\{\left(\mathbf{H}, \mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right),\left(\mathbf{e}_{I}, I\right) \mid \text { for some } I \in[N], \mathbf{s}_{I}^{\top}=\mathbf{H e}_{I}^{\top}, \mathbf{e}_{I} \in B(n, t)\right\} \tag{1}
\end{equation*}
$$

where $\mathbf{H} \in \mathbb{F}_{2}^{(n-k) \times n}$ and $\mathbf{s}_{i} \in \mathbb{F}_{2}^{n-k}$ for all $i \in[N]$.
Our idea stems from a key observation that in the modified Stern protocol in Fig. 1, the commitment $c_{1}=\operatorname{Com}\left(\delta, \mathbf{H r}^{\top}+\mathbf{s}^{\top} ; \rho_{1}\right)$ needs to be verified in two different ways, in which one is related to the syndrome $\mathbf{s}$ while the other is unrelated to $\mathbf{s}$. Based on this, we replace $c_{1}$ with the following set

$$
\left(\operatorname{Com}\left(\delta, \mathbf{H r}^{\top}+\mathbf{s}_{1}^{\top} ; b_{1}\right), \cdots, \operatorname{Com}\left(\delta, \mathbf{H r}^{\top}+\mathbf{s}_{N}^{\top} ; b_{N}\right)\right)
$$

while keeping $c_{2}$ and $c_{3}$ unchanged, and compress it into a root using an indexhiding Merkle tree. Then, the root, $c_{2}$ and $c_{3}$ are sent to a verifier.

When the challenge is 1 , the verifier checks $c_{2}$ and $c_{3}$ as the original Stern protocol. When the challenge is 2 , the verifier checks the root and $c_{3}$ by using the path of the index-hiding Merkle tree, $\mathbf{r}+\mathbf{e}_{I}$ and $\delta$. When the challenge is 3, the verifier calculates all leaf nodes using $\mathbf{r}$ and checks the root and $c_{2}$ by leaf nodes and $\delta$.

In the following we first show that our protocol in Fig. 2 satisfies perfect completeness. That is, if $\mathcal{P}$, which possesses the witness $\left(\mathbf{e}_{I}, I\right)$, faithfully executes the protocol, $\mathcal{V}$ will output "accept" with a probability of 1 . If $c h=1, \mathcal{V}$ only needs to repeat the calculation process of $c_{2}$ and $c_{3}$, and so it always outputs "accept". If $c h=2, \mathcal{V}$ needs to reconstruct the root using the $I$-th leaf node and repeat the calculation process of $c_{3}$. The reconstructed root is the same as the one constructed using all leaves, and hence it always outputs "accept". If $c h=3, \mathcal{V}$ only needs to repeat the calculation process of the root and $c_{2}$, and also it always outputs "accept".

Next, the following Theorems 1 and 2 state that our protocol in Fig. 2 is sound and zero-knowledge.

Theorem 1. Assuming that Com is a computational binding commitment scheme and the hash function $\mathcal{H}$ used in the Merkle tree is collision-resistant, the protocol in Fig. 2 is an argument of knowledge with soundness error 2/3.

Proof. Assuming there is an adversary $\mathcal{A}$ who is accepted with a probability greater than $2 / 3$, i.e., $\mathcal{A}$ can effectively respond all three challenges. Then, we can construct an extractor $\mathcal{E}$ which either breaks the binding property of Com, or outputs a collision in $\mathcal{H}$, or $\mathbf{e} \in B(n, t)$ such that $\mathbf{H e}^{\top}=\mathbf{s}_{I}^{\top}$ for a certain $I \in[N]$. Formally, given a $\operatorname{CMT}\left(c_{1}, c_{2}, c_{3}\right)$ and its three valid responses

$$
\operatorname{RSP}_{1}=\left(\mathbf{w}_{1}, \mathbf{w}_{2}, \rho_{2}, \rho_{3}\right), \operatorname{RSP}_{2}=\left(\mathbf{w}_{3}, \xi_{\delta}, b, \text { path }, \rho_{3}\right), \operatorname{RSP}_{3}=\left(\xi_{s}, \xi_{r}, \xi_{\delta}^{\prime}, \rho_{2}\right)
$$

each of them corresponds to distinct challenges $c h=1, c h=2$ and $c h=3$ respectively. $\mathcal{E}$ first calculates

Due to the validity of these responses, we have

$$
\left\{\begin{array}{l}
c_{1}=\mathrm{R}_{1}^{\prime}=\mathrm{R}_{2}^{\prime}, \mathbf{w}_{2} \in B(n, t) ; \\
c_{2}=\operatorname{Com}\left(\mathbf{w}_{1} ; \rho_{2}\right)=\operatorname{Com}\left(\pi_{2}\left(\mathbf{p}_{1}\right) ; \rho_{2}\right) ; \\
c_{3}=\operatorname{Com}\left(\mathbf{w}_{1}+\mathbf{w}_{2} ; \rho_{3}\right)=\operatorname{Com}\left(\pi_{1}\left(\mathbf{w}_{3}\right) ; \rho_{3}\right) .
\end{array}\right.
$$

Then, $\mathcal{E}$ checks if $\left(\mathbf{w}_{1}, \rho_{2}\right) \neq\left(\pi_{2}\left(\mathbf{p}_{1}\right), \rho_{2}\right)$. If so, $\mathcal{E}$ breaks the binding property of Com. Similarly, $\mathcal{E}$ checks if $\left(\mathbf{w}_{1}+\mathbf{w}_{2}, \rho_{3}\right) \neq\left(\pi_{1}\left(\mathbf{w}_{3}\right), \rho_{3}\right)$. If neither of these two inequalities holds true, we have

$$
\begin{equation*}
\mathbf{w}_{1}=\pi_{2}\left(\mathbf{p}_{1}\right), \mathbf{w}_{1}+\mathbf{w}_{2}=\pi_{1}\left(\mathbf{w}_{3}\right) \tag{2}
\end{equation*}
$$

Next, $\mathcal{E}$ checks if $\operatorname{Com}\left(\pi_{1}, \mathbf{H w}_{3}^{\top} ; b\right) \neq$ leaf $_{i}^{\prime}$ for $\forall i \in[N]$. If so, it finds a collision in $\mathcal{H}$ by employing the Merkle tree extractor in Lemma 1 with the input (tree, $\operatorname{Com}\left(\pi_{1}, \mathbf{H} \mathbf{w}_{3}^{\top} ; b\right)$, path). Otherwise, there exists an index $I \in[N]$ satisfying $\operatorname{Com}\left(\pi_{1}, \mathbf{H w}_{3}^{\top} ; b\right)=$ leaf $_{I}^{\prime}$. Furthermore, $\mathcal{E}$ checks if $\left(\pi_{1}, \mathbf{H w}_{3}^{\top}, b\right) \neq$ $\left(\pi_{2}, \mathbf{H} \mathbf{p}_{1}^{\top}+\mathbf{s}_{I}^{\top}, b_{I}\right)$. If so, $\mathcal{E}$ breaks the binding property of Com. Otherwise, $\mathcal{E}$ gets $\pi_{1}=\pi_{2}, \mathbf{H w}_{3}^{\top}=\mathbf{H} \mathbf{p}_{1}^{\top}+\mathbf{s}_{I}^{\top}$ and $b=b_{I}$. From this and Eq. (2), we deduce that $\mathbf{H} \pi_{1}^{-1}\left(\mathbf{w}_{2}^{\top}\right)=\mathbf{s}_{I}^{\top}$, where $\pi_{1}^{-1}\left(\mathbf{w}_{2}\right) \in B(n, t)$. This means that $\mathcal{E}$ outputs the witness $\mathbf{e}=\pi_{1}^{-1}\left(\mathbf{w}_{2}\right) \in B(n, t)$ such that $\mathbf{H e}=\mathbf{s}_{I}, I \in[N]$.

Theorem 2. The protocol in Fig. 2 is honest-verifier zero-knowledge, that is, there exists a simulator Sim, such that for any statement-witness pair $(s, w)$ belonging to the relation (1), any ch $\in\{1,2,3\}$ and any adversary $\mathcal{A}$ that accesses the oracle $\mathcal{Q}$ times, the following holds

$$
\left|\operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\mathcal{P}(s, w, c h)) \rightarrow 1\right]-\operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\operatorname{Sim}(s, c h)) \rightarrow 1\right]\right| \leq \frac{2 \mathcal{Q}}{2^{\lambda}}
$$

Round 1: $\mathcal{P}_{1}^{h}\left(\left(\mathbf{H}, \mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right),\left(\mathbf{e}_{I}, I\right)\right)$ :

- $\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\zeta_{s}, N\right)$.
- leaf $=\left(\operatorname{Com}\left(\delta, \mathbf{H r}^{\top}+\mathbf{s}_{1}^{\top} ; b_{1}\right), \cdots, \operatorname{Com}\left(\delta, \mathbf{H r}^{\top}+\mathbf{s}_{N}^{\top} ; b_{N}\right)\right)$.
$-($ root, tree $)=\mathrm{IH}-$ Mtree(leaf).
- Send CMT $:=\left(c_{1}, c_{2}, c_{3}\right)$ to $\mathcal{V}$, where

$$
c_{1}=\operatorname{root}, c_{2}=\operatorname{Com}\left(\delta(\mathbf{r}) ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\delta\left(\mathbf{r}+\mathbf{e}_{I}\right) ; \rho_{3}\right) .
$$

Round 2: $\mathcal{V}_{1}^{h}$ (CMT) sends a $c h \stackrel{\&}{\leftarrow}\{1,2,3\}$ to $\mathcal{P}$.
Round 3: $\mathcal{P}_{2}^{h}\left(\left(\mathbf{H}, \mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right),\left(\mathbf{e}_{I}, I\right), c h\right)$ :

- Case $c h=1$ : Set $\mathbf{w}_{1}=\delta(\mathbf{r}), \mathbf{w}_{2}=\delta\left(\mathbf{e}_{I}\right)$.

Send RSP $=\left(\mathbf{w}_{1}, \mathbf{w}_{2}, \rho_{2}, \rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=2:$ Set $\mathbf{w}_{3}=\mathbf{r}+\mathbf{e}_{I}, \xi_{\delta}=\zeta_{\delta}, b=b_{I}$, path $=\operatorname{Gpath}(\operatorname{tree}, I)$.

Send RSP $=\left(\mathbf{w}_{3}, \xi_{\delta}, b\right.$, path, $\left.\rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=3:$ Set $\xi_{s}=\zeta_{s}, \xi_{r}=\zeta_{r}, \xi_{\delta}^{\prime}=\zeta_{\delta}$.

Send RSP $=\left(\xi_{s}, \xi_{r}, \xi_{\delta}^{\prime}, \rho_{2}\right)$ to $\mathcal{V}$.
Verification: $\mathcal{V}_{2}^{h}\left(\left(\mathbf{H}, \mathbf{s}_{1}, \cdots, \mathbf{s}_{N}\right), \mathrm{CMT}, c h, \operatorname{RSP}\right)$ :

- Case $c h=1$ : Check if $\mathbf{w}_{2} \in B(n, t)$ and

$$
c_{2}=\operatorname{Com}\left(\mathbf{w}_{1} ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\mathbf{w}_{1}+\mathbf{w}_{2} ; \rho_{3}\right) .
$$

- Case $c h=2$ : Set $\pi_{1} \stackrel{\Phi_{i}, \xi_{\delta}}{\leftrightarrows} \mathcal{S}_{n}, \mathrm{R}_{1}=\operatorname{Rebuild}\left(\right.$ path, $\left.\operatorname{Com}\left(\pi_{1}, \mathbf{H w}_{3}^{\top} ; b\right)\right)$, and check if

$$
c_{1}=\mathrm{R}_{1}, c_{3}=\operatorname{Com}\left(\pi_{1}\left(\mathbf{w}_{3}\right) ; \rho_{3}\right) .
$$

- Case $c h=3: \operatorname{Set}\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\xi_{s}, N\right), \mathbf{p}_{1} \stackrel{\S, \xi_{r}}{\leftrightarrows} \mathbb{F}_{2}^{n}, \pi_{2} \stackrel{\Phi, \xi_{\delta}^{\prime}}{\leftrightarrows} \mathcal{S}_{n}$ and leaf $=\left(\operatorname{Com}\left(\pi_{2}, \mathbf{H p}_{1}^{\top}+\mathbf{s}_{1}^{\top} ; b_{1}\right), \cdots, \operatorname{Com}\left(\pi_{2}, \mathbf{H} \mathbf{p}_{1}^{\top}+\mathbf{s}_{N}^{\top} ; b_{N}\right)\right)$.

Compute $\mathrm{R}_{2}$ as IH-Mtree(leaf) and check if

$$
c_{1}=\mathrm{R}_{2}, c_{2}=\operatorname{Com}\left(\pi_{2}\left(\mathbf{p}_{1}\right) ; \rho_{2}\right) .
$$

$\mathcal{V}$ outputs 1 when all conditions are met, else it outputs 0 .
Fig. 2. The SD-based one-out-of-many proof $\Pi^{h}=\left(\mathcal{P}^{h}=\left(\mathcal{P}_{1}^{h}, \mathcal{P}_{2}^{h}\right), \mathcal{V}^{h}=\left(\mathcal{V}_{1}^{h}, \mathcal{V}_{2}^{h}\right)\right)$.

Proof. To simplify the proof, we use the random oracle $\mathcal{O}^{*}(\cdot)$ to instantiate the hash function, the algorithm Stree, and Com, where $*$ denotes the instantiated object. The simulator Sim is constructed as follows:
Case $c h=1$ :

1. Sim selects the following random objects:

$$
\mathbf{w}_{1} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{n}, \mathbf{w}_{2} \stackrel{\$}{\leftarrow} B(n, t),\left\{\rho_{2}, \rho_{3}\right\} \stackrel{\$}{\leftarrow}\{0,1\}^{\lambda}, c_{1} \stackrel{\$}{\leftarrow}\{0,1\}^{2 \lambda} .
$$

2. $\operatorname{Sim}$ lets $\mathrm{CMT}=\left(c_{1}^{\prime}, c_{2}^{\prime}, c_{3}^{\prime}\right)$, where

$$
c_{1}^{\prime}=c_{1}, c_{2}^{\prime}=\operatorname{Com}\left(\mathbf{w}_{1} ; \rho_{2}\right), c_{3}^{\prime}=\operatorname{Com}\left(\mathbf{w}_{\mathbf{1}}+\mathbf{w}_{2} ; \rho_{3}\right) .
$$

3. Sim lets RSP $=\left(\mathbf{w}_{1}, \mathbf{w}_{2}, \rho_{2}, \rho_{3}\right)$ and returns $(\mathrm{CMT}, 1, \mathrm{RSP})$.

Case $c h=2$ :

1. Sim selects the following random objects:

$$
\mathbf{w}_{3} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{n},\left\{b, \xi_{\delta}, \rho_{3},\left\{\operatorname{leaf}_{i}\right\}_{i=2}^{N}\right\} \stackrel{\$}{\leftarrow}\{0,1\}^{\lambda}, c_{2} \stackrel{\$}{\leftarrow}\{0,1\}^{2 \lambda}, \pi_{1} \stackrel{\$, \xi_{\delta}}{\leftrightarrows} \mathcal{S}_{n} .
$$

2. $\operatorname{Sim}$ sets leaf ${ }_{1}=\operatorname{Com}\left(\pi_{1}, \mathbf{H w}_{3}^{\top} ; b\right)$ and obtains (tree, root) $=\mathrm{IH}$-Mtree(leaf).
3. Sim lets $\mathrm{CMT}=\left(c_{1}^{\prime}, c_{2}^{\prime}, c_{3}^{\prime}\right)$, where

$$
c_{1}^{\prime}=\operatorname{root}, c_{2}^{\prime}=c_{2}, c_{3}^{\prime}=\operatorname{Com}\left(\pi_{1}\left(\mathbf{w}_{3}\right) ; \rho_{3}\right)
$$

4. Sim runs the algorithm GPath(tree, 1) to retrieve the path.
5. Sim lets RSP $=\left(\mathbf{w}_{3}, \xi_{\delta}, b\right.$, path, $\left.\rho_{3}\right)$ and returns $(\mathrm{CMT}, 2, \mathrm{RSP})$.

Case $c h=3$ :

1. Sim selects the following random objects:

$$
\left\{\xi_{s}, \xi_{r}, \xi_{\delta}, \rho_{2}\right\} \stackrel{\$}{\leftrightarrows}\{0,1\}^{\lambda}, c_{3} \stackrel{\$}{\leftarrow}\{0,1\}^{2 \lambda}, \mathbf{v}_{2} \stackrel{\Phi, \xi_{r}}{\leftrightarrows} \mathbb{F}_{2}^{n}, \pi_{2} \stackrel{\Phi, \xi_{\delta}}{\leftrightarrows} \mathcal{S}_{n} .
$$

2. Sim sets leaf $=\left(\operatorname{Com}\left(\mathbf{H} \mathbf{p}_{1}^{\top}+\mathbf{s}_{1}^{\top} ; b_{1}\right), \cdots, \operatorname{Com}\left(\mathbf{H} \mathbf{p}_{1}^{\top}+\mathbf{s}_{N}^{\top} ; b_{N}\right)\right)$ and calculates its root, where $\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\xi_{\mathrm{s}}, N\right)$.
3. Sim lets CMT $=\left(c_{1}^{\prime}, c_{2}^{\prime}, c_{3}^{\prime}\right)$, where

$$
c_{1}^{\prime}=\operatorname{root}, c_{2}^{\prime}=\operatorname{Com}\left(\pi_{2}\left(\mathbf{v}_{2}\right) ; \rho_{2}\right), c_{3}^{\prime}=c_{3}
$$

4. Sim lets RSP $=\left(\xi_{s}, \xi_{r}, \xi_{\delta}, \rho_{2}\right)$ and returns (CMT, 3, RSP).

If Com is statistically hiding, then two CMTs generated by Sim and a honest prover, respectively, are statistically indistinguishable. Therefore, we only need to check the case of RSP.
$c h=1$ : Since Sim draws $\left(\mathbf{w}_{1}, \mathbf{w}_{2}\right)$ at random from $\mathbb{F}_{2}^{n} \times B(n, t)$, both RSPs generated by a honest prover and Sim respectively, follow the random distribution on $\mathbb{F}_{2}^{n} \times B(n, t)$.
$c h=2$ : Set five simulators $\left\{\operatorname{Sim}_{i}\right\}_{i=1}^{5}$ to prove that Sim and a honest prover are indistinguishable. $\operatorname{Sim}_{1}$ and $\operatorname{Sim}_{5}$ represent a honest prover and Sim, respectively. Let $E_{i}$ denote $\mathcal{A}^{\mathcal{O}}\left(\operatorname{Sim}_{i}(s, c h)\right)=1$, for $i \in[5]$.
$\operatorname{Sim}_{2}$ : The only difference between $\operatorname{Sim}_{2}$ and $\operatorname{Sim}_{1}$ is that $\left\{b_{i}\right\}_{i=1}^{N}$ are randomly sampled from $\{0,1\}^{\lambda}$ instead of being generated by the $\mathcal{O}^{\text {Stree }}(\cdot)$ algorithm Stree with an input $\zeta_{s}$. If $\zeta_{s}$ has not been queried by $\mathcal{A}$ to the oracle $\mathcal{O}^{\text {Stree }}(\cdot)$, $\operatorname{Sim}_{2}$ and $\operatorname{Sim}_{1}$ are indistinguishable. Thus, if $\mathcal{O}^{\text {Stree }}(\cdot)$ is accessed $\mathcal{Q}$ times and the probability of colliding with $\zeta_{s}$ is $2^{\lambda}$ for each query, the probability of colliding with $\zeta_{s}$ after $\mathcal{Q}$ queries is $\mathcal{Q} / 2^{\lambda}$. Thus, we have $\left|\operatorname{Pr}\left[E_{2}\right]-\operatorname{Pr}\left[E_{1}\right]\right| \leq \mathcal{Q} / 2^{\lambda}$.
$\operatorname{Sim}_{3}$ : The only difference between $\operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ is that $\left\{\operatorname{leaf}_{i}\right\}_{i=1, i \neq I}^{N}$ are randomly sampled from $\{0,1\}^{2 \lambda}$ instead of being generated by $\mathcal{O}^{\text {Com }}(\cdot)$ with the tuple $\left(\pi_{1}, \mathbf{H r}^{\top}+\mathbf{s}_{i}^{\top} ; b_{i}\right)$ for $i \neq I$. If all tuples have not been queried by $\mathcal{A}$ to the oracle $\mathcal{O}^{\mathrm{Com}}(\cdot), \operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ are indistinguishable. We use $\mathcal{Q}_{\mathrm{com}_{i}}$ to
represent the number of times $\mathcal{O}^{\mathrm{Com}_{i}}(\cdot)$ is accessed. Since the minimum entropy of $b_{i}$ is $1 / 2^{\lambda}$, the minimum entropy of tuple ( $\left.\pi_{1}, \mathbf{H r}^{\top}+\mathbf{s}_{i}^{\top} ; b_{i}\right)$ is at most $1 / 2^{\lambda}$. Therefore, the probability of collision with the tuple in each query is at most $1 / 2^{\lambda}$. Furthermore, since $\sum_{i=1}^{N} \mathcal{Q}_{\text {leaf }_{i}} \leq \mathcal{Q}$, we have $\left|\operatorname{Pr}\left[E_{3}\right]-\operatorname{Pr}\left[E_{2}\right]\right| \leq Q / 2^{\lambda}$.

Sim $_{4}$ : There are two differences between $\operatorname{Sim}_{4}$ and $\operatorname{Sim}_{3}$. Firstly, $c_{3}$ is randomly sampled from $\{0,1\}^{2 \lambda}$. Secondly, leaf ${ }_{I}=\operatorname{Com}\left(\pi_{1}, \mathbf{H w}_{3}^{\top} ; b_{I}\right)$, where $\mathbf{w}_{3}$ is randomly sampled from $\mathbb{F}_{2}^{n}$. Since $\mathbf{w}_{3}$ and $c_{3}$ follows the random distribution as the real transcript, we have $\operatorname{Pr}\left[E_{4}\right]=\operatorname{Pr}\left[E_{3}\right]$.
$\operatorname{Sim}_{5}$ : The only difference between $\operatorname{Sim}_{5}$ and $\operatorname{Sim}_{4}$ is that 1 is used instead of $I$ in witness. Lemma 2 states that regardless of whether the selected index is 1 or $I$, the root and path follow the same distribution. Therefore, we have $\operatorname{Pr}\left[E_{5}\right]=\operatorname{Pr}\left[E_{4}\right]$.

Thus, we have $\left|\operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\mathcal{P}(s, w, 2)) \rightarrow 1\right]-\operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\operatorname{Sim}(s, 2)) \rightarrow 1\right]\right| \leq \frac{2 \mathcal{Q}}{2^{\lambda}}$.
$c h=3$ : Since a honest prover does not use the witness, Sim can perfectly simulate RSP.

In summary, we obtain the required result.

### 3.2 The GSD-Based One-out-of-Many Proof

We first propose a GSD-based one-out-of-many proof in one-iteration in Fig. 3. This protocol is for the following relation:
$R=\left\{\left(\mathbf{G},\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}\right),(\mathbf{x}, \mathbf{e}, I) \mid\right.$ forsome $\left.I \in[N], \mathbf{y}_{I}=\mathbf{x} \mathbf{G}+\mathbf{e}, \mathbf{x} \in \mathbb{F}_{2}^{k}, \mathbf{e} \in B(n, t)\right\}$,
where $\mathbf{G} \in \mathbb{F}_{2}^{k \times n}$ and $\mathbf{y}_{i} \in \mathbb{F}_{2}^{n}$ for all $i \in[N]$. Next, we present its multi-iteration version in Fig. 4 by using additional optimization techniques such as commitments compression [23,31], seedtrees [6,23] and small-weight vector compression functions [31]. In the following we first explain how to use them to obtain the multi-iteration version, which is called the GSD-based one-out-of-many proof.

Commitments Compression: The soundness error of the GSD-based one-out-of-many proof in one-iteration in Fig. 3 is $2 / 3$, and so this protocol needs to be repeated $\kappa$ times to reduce the soundness error. Since three commitments $\left(c_{1}^{j}, c_{2}^{j}, c_{3}^{j}\right), j \in[\kappa]$ need to be output in each iteration, the total cost of commitments is $3 \kappa \mid$ Com $\mid$. To reduce the total cost of commitments, we optimize the above protocol by using three Merkle trees Tree $_{1}$, Tree $_{2}$ and Tree 3 to compress $\left(c_{1}^{1}, \cdots, c_{1}^{\kappa}\right),\left(c_{2}^{1}, \cdots, c_{2}^{\kappa}\right)$ and $\left(c_{3}^{1}, \cdots, c_{3}^{\kappa}\right)$ as $\operatorname{root}_{1}$, root $_{2}$ and $\operatorname{root}_{3}$ respectively, where $\left(c_{1}^{j}, c_{2}^{j}, c_{3}^{j}\right)$ denotes the commitment of the j -th iteration. The prover sends CMT $=\mathcal{H}\left(\operatorname{root}_{1}\right.$, root $\left._{2}, \operatorname{root}_{3}\right)$. Since the verifier can reconstruct two out of the three commitments $\left(c_{1}^{j}, c_{2}^{j}, c_{3}^{j}\right)$ in each iteration, the prover transmits those commitments that cannot be computed by the verifier through certain intermediate nodes of the tree. In summary, this will reduce the cost of commitments from $3 \kappa \mid$ Com $\mid$ to $|\mathcal{H}|+\frac{5 \kappa|\mathrm{Com}|}{6}$.
Seedtrees: In one-iteration protocol, a set of seeds needs to be generated for sampling random objects and so certain seeds are revealed based on the challenge. To reduce the communication cost of seeds, we use a set of master seeds
along with a set of seedtrees to generate $\kappa$ sets of seeds in $\kappa$ iterations. During the response phase, we provide those revealed seeds by outputting certain intermediate nodes in the seedtree. If the probability of a seed being transmitted in one iteration is $1 / p$, then using a seedtree reduces the transmission cost of this seed by about $1 / 2 p$.

Small-Weight Vector Compression: Since the protocol in Fig. 3 may transmit a small weight vector, we employ a small vector compression function in multi-iteration version to reduce the cost of transmitting small weight vectors from $n$ to approximately $n / 2$.

By using the above optimization techniques, a multi-iteration version is proposed in Fig. 4. As mentioned in [6], to ensure a tighter security proof and avoid multi-target attacks [14], we use a "salt", a $2 \lambda$-bit prefix string, in these seedtrees to distinguish the random oracles used in the seedtrees of different iterations. The "salt" has a negligible impact on practice.

The following theorem provides the security of the protocol in Fig. 4.
Theorem 3. The protocol described in Fig. 4 is an argument of knowledge with the perfect completeness and honest-verifier zero-knowledge.

Proof. Completeness: This protocol has perfect completeness, which is immediately obtained by the correctness of the seedtrees, Merkle trees, and indexhiding Merkle trees.
Soundness: Assume there is an adversary $\mathcal{A}$ who is accepted with a probability $>(2 / 3)^{\kappa}$, i.e., $\mathcal{A}$ is able to successfully answer all three challenges in some iteration $j$ where $j \in[\kappa]$. We build an extractor $\mathcal{E}$ which either breaks the binding property of Com, or outputs a collision in $\mathcal{H}$, or outputs $\mathbf{x} \in \mathbb{F}_{2}^{k}, \mathbf{e} \in B(n, t)$ such that $\mathbf{x G}+\mathbf{e}=\mathbf{y}_{I}$ for some $I \in[N]$. First, $\mathcal{E}$ obtains the seeds, random coins and the commitment of the $j$-th iteration by $\mathrm{RSP}_{1}, \mathrm{RSP}_{2}, \mathrm{RSP}_{3}$ and the algorithms of seedtrees and Merkle trees.

$$
\left\{\xi_{s}^{j}, \xi_{u}^{j}, \xi_{\delta}^{j}, \xi_{\delta^{\prime}}^{j}, \rho_{1}^{j}, \rho_{2}^{j}, c_{1}^{j}, c_{2}^{j}, c_{3}^{j}\right\} \longleftarrow\left(\mathrm{RSP}_{1}, \mathrm{RSP}_{2}, \mathrm{RSP}_{3}\right)
$$

Then, $\mathcal{E}$ performs the following steps:

Due to the validity of these responses, we have

$$
\left\{\begin{array}{l}
c_{1}^{j}=\mathrm{R}_{1}^{j}=\mathrm{R}_{2}^{j}, \mathbf{w}_{3}^{j} \in B(n, t) ; \\
c_{2}^{j}=\operatorname{Com}\left(\pi_{1}^{j}, \mathbf{p}_{1}^{j} ; \rho_{2}^{j}\right)=\operatorname{Com}\left(\pi_{2}^{j}, \mathbf{p}_{3}^{j} ; \rho_{2}^{j}\right) ; \\
c_{3}^{j}=\operatorname{Com}\left(\mathbf{w}_{2}^{j}, \rho_{3}^{j}\right)=\operatorname{Com}\left(\pi_{1}^{j}\left(\mathbf{w}_{1}^{j} \mathbf{G}_{1}\right)+\mathbf{p}_{1}^{j} ; \rho_{3}^{j}\right) .
\end{array}\right.
$$

Round 1: $\mathcal{P}_{1}^{g}\left(\left(\mathbf{G}, \mathbf{y}_{1}, \cdots, \mathbf{y}_{N}\right),(I, \mathbf{x}, \mathbf{e})\right)$ chooses the following random objects:

```
    \(\left\{\zeta_{s}, \zeta_{u}, \zeta_{\delta}, \rho_{1}, \rho_{2}\right\} \stackrel{\S}{\leftarrow}\{0,1\}^{\lambda} ; \mathbf{u} \stackrel{\Phi_{,}, \zeta_{u}}{\leftarrow} \mathbb{F}_{2}^{k}, \mathbf{v} \stackrel{\Phi, \zeta_{\delta}}{\leftarrow} \mathbb{F}_{2}^{n}, \delta \stackrel{\Phi, \zeta_{\delta}}{\leftrightarrows} \mathcal{S}_{n}\).
    - \(\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\zeta_{s}, N\right)\).
    - leaf \(=\left(\operatorname{Com}\left(\delta\left(\mathbf{u G}+\mathbf{y}_{1}\right)+\mathbf{v} ; b_{1}\right), \cdots, \operatorname{Com}\left(\delta\left(\mathbf{u G}+\mathbf{y}_{N}\right)+\mathbf{v} ; b_{N}\right)\right)\).
    - (root, tree) \(=\) IH-Mtree(leaf).
    - Send CMT \(:=\left(c_{1}, c_{2}, c_{3}\right)\) to \(\mathcal{V}\), where
```

$$
c_{1}=\operatorname{root}, c_{2}=\operatorname{Com}\left(\delta, \mathbf{v} ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\delta((\mathbf{u}+\mathbf{x}) \mathbf{G})+\mathbf{v} ; \rho_{3}\right) .
$$

Round 2: $\mathcal{V}_{1}^{g}(\mathrm{CMT})$ sends a challenge $c h \stackrel{\$}{\leftarrow}\{1,2,3\}$ to $\mathcal{P}$.
Round 3: $\mathcal{P}_{2}^{g}\left(\left(\mathbf{G}, \mathbf{y}_{1}, \cdots, \mathbf{y}_{N}\right),(I, \mathbf{x}, \mathbf{e})\right.$, ch) responds as follows:

- Case $c h=1$ : Set $\xi_{\delta}^{\prime}=\zeta_{\delta}, \mathbf{w}_{1}=\mathbf{u}+\mathbf{x}$.

Send RSP $=\left(\xi_{\delta}^{\prime}, \mathbf{w}_{1}, \rho_{2}, \rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=2$ : Set

$$
\mathbf{w}_{2}=\delta((\mathbf{u}+\mathbf{x}) \mathbf{G})+\mathbf{v}, \mathbf{w}_{3}=\delta(\mathbf{e}) ; b=b_{I}, \text { path }=\operatorname{Gpath}(\text { tree }, I) .
$$

Send RSP $=\left(\mathbf{w}_{2}, \mathbf{w}_{3}, b\right.$, path, $\left.\rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=3$ : Set $\xi_{s}=\zeta_{s}, \xi_{u}=\zeta_{u}, \xi_{\delta}=\zeta_{\delta}$.

Send RSP $=\left(\xi_{s}, \xi_{u}, \xi_{\delta}, \rho_{2}\right)$ to $\mathcal{V}$.
Verification: $\mathcal{V}_{2}^{g}\left(\left(\mathbf{G}, \mathbf{y}_{1}, \cdots, \mathbf{y}_{N}\right), \mathrm{CMT}\right.$, ch, RSP) proceeds as follows:

- Case $c h=1:$ Set $\mathbf{p}_{1} \stackrel{\Phi, \xi_{\delta}^{\prime}}{\leftarrow} \mathbb{F}_{2}^{n}, \pi_{1} \stackrel{\S, \xi_{\delta}^{\prime}}{\leftrightarrows} \mathcal{S}_{n}$ and check if

$$
c_{2}=\operatorname{Com}\left(\pi_{1}, \mathbf{p}_{1} ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\pi_{1}\left(\mathbf{w}_{1} \mathbf{G}_{1}\right)+\mathbf{p}_{1} ; \rho_{3}\right) .
$$

- Case $c h=2$ : Compute $\mathrm{R}_{1}$ as Rebuild(path, $\operatorname{Com}\left(\mathbf{w}_{2}+\mathbf{w}_{3} ; b\right)$ ), Check if $\mathbf{w}_{3} \in B(n, t)$ and

$$
c_{1}=\mathrm{R}_{1}, c_{3}=\operatorname{Com}\left(\mathbf{w}_{2} ; \rho_{3}\right) .
$$


$\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\xi_{s}, N\right)$.

$$
\text { leaf }=\left(\operatorname{Com}\left(\pi_{2}\left(\mathbf{p}_{2} \mathbf{G}_{1}+\mathbf{y}_{1}\right)+\mathbf{p}_{3} ; b_{1}\right), \cdots, \operatorname{Com}\left(\pi_{2}\left(\mathbf{p}_{2} \mathbf{G}_{1}+\mathbf{y}_{N}\right)+\mathbf{p}_{3} ; b_{N}\right)\right)
$$

Obtain $\mathrm{R}_{2}$ as IH-Mtree(leaf) and check if

$$
c_{1}=\mathrm{R}_{2}, c_{2}=\operatorname{Com}\left(\pi_{2}, \mathbf{p}_{3} ; \rho_{2}\right) .
$$

$\mathcal{V}$ outputs 1 when all conditions are met, else it outputs 0 .
Fig. 3. The one-iteration GSD-based one-out-of-many proof $\Pi^{g}=\left(\mathcal{P}^{g}=\left(\mathcal{P}_{1}^{g}, \mathcal{P}_{2}^{g}\right)\right.$, $\left.\mathcal{V}^{g}=\left(\mathcal{V}_{1}^{g}, \mathcal{V}_{2}^{g}\right)\right)$.
$\mathcal{E}$ first checks if $\left(\pi_{1}^{j}, \mathbf{p}_{1}^{j}, \rho_{2}^{j}\right) \neq\left(\pi_{2}^{j}, \mathbf{p}_{3}^{j}, \rho_{2}^{j}\right)$. If so, $\mathcal{E}$ breaks the binding property of Com. Similarly, $\mathcal{E}$ checks if $\left(\mathbf{w}_{2}^{j}, \rho_{3}^{j}\right) \neq\left(\pi_{1}^{j}\left(\mathbf{w}_{1}^{j} \mathbf{G}_{1}\right)+\mathbf{p}_{1}^{j}, \rho_{3}^{j}\right)$. If neither of these two inequalities holds true, we have

$$
\begin{equation*}
\pi_{1}^{j}=\pi_{2}^{j}, \mathbf{p}_{1}^{j}=\mathbf{p}_{3}^{j}, \mathbf{w}_{2}^{j}=\pi_{1}^{j}\left(\mathbf{w}_{1}^{j} \mathbf{G}_{1}\right)+\mathbf{p}_{1}^{j} . \tag{4}
\end{equation*}
$$

Round 1: $\mathcal{P}_{1}^{\text {oom }}\left(\left(\mathbf{G},\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}\right),(I, \mathbf{x}, \mathbf{e})\right)$ chooses the following random objects:

$$
\begin{aligned}
& \left\{\zeta_{s}^{\text {root }}, \zeta_{u}^{\text {root }}, \zeta_{\delta}^{\text {root }}, \rho_{1}^{\text {root }}, \rho_{2}^{\text {root }}\right\} \stackrel{\$}{\leftarrow}\{0,1\}^{\lambda}, \theta \stackrel{\$}{\leftarrow}\{0,1\}^{2 \lambda} . \\
& -\left(\left\{\zeta_{s}^{i}\right\}_{i=1}^{\kappa}\right)=\operatorname{Stree}\left(\zeta_{s}^{\text {root }}, \kappa\right),\left(\left\{\zeta_{u}^{i}\right\}_{i=1}^{\kappa}\right)=\operatorname{Stree}\left(\zeta_{u}^{\text {root }}, \kappa\right),\left(\left\{\zeta_{\delta}^{i}\right\}_{i=1}^{\kappa}\right)=\operatorname{Stree}\left(\zeta_{\delta}^{\text {root }}, \kappa\right) \text {. } \\
& \text { - }\left(\left\{\rho_{1}^{i}\right\}_{i=1}^{\kappa}\right)=\operatorname{Stree}\left(\rho_{1}^{\text {root }}, \kappa\right),\left(\left\{\rho_{2}^{i}\right\}_{i=1}^{\kappa}\right)=\operatorname{Stree}\left(\rho_{2}^{\text {root }}, \kappa\right) \text {. } \\
& \text { - For } j \text { from } 1 \text { to } \kappa \text { do } \\
& \left(c_{1}^{j}, c_{2}^{j}, c_{3}^{j}\right) \leftarrow \mathcal{P}_{1}^{g}\left(\left(\mathbf{G},\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}\right),(I, \mathbf{x}, \mathbf{e}),\left(\zeta_{s}^{j}, \zeta_{u}^{j}, \zeta_{\delta}^{j}, \rho_{1}^{j}, \rho_{2}^{j}\right), \theta\right) . \\
& \left(\operatorname{Mtree}_{1}, C_{1}\right)=\operatorname{Mtree}\left(c_{1}^{1}, \cdots, c_{1}^{\kappa}\right),\left(\operatorname{Mtree}_{2}, C_{2}\right)=\operatorname{Mtree}\left(c_{2}^{1}, \cdots, c_{2}^{\kappa}\right) \text {, } \\
& \left(\operatorname{Mtree}_{3}, C_{3}\right)=\operatorname{Mtree}\left(c_{3}^{1}, \cdots, c_{3}^{\kappa}\right) \text {. }
\end{aligned}
$$

- Send CMT $:=\left(\mathcal{H}\left(C_{1}, C_{2}, C_{3}\right), \theta\right)$ to $\mathcal{V}$.

Round 2: $\mathcal{V}_{1}^{\text {oom }}(\mathrm{CMT})$ sends a challenge $\mathbf{c h}=\left(c h_{1}, \cdots, c h_{\kappa}\right) \stackrel{\$}{\leftarrow}\{1,2,3\}^{\kappa}$ to $\mathcal{P}$.
Round 3: $\mathcal{P}_{2}^{\text {oom }}\left(\left(\mathbf{G},\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}\right),(I, \mathbf{x}, \mathbf{e}), \mathbf{c h}\right)$ responds as follows:

- path $_{1}=$ Gpath $\left(\right.$ Mtree $\left._{1},\{j\}_{c h^{j}=1}\right)$.
- $\operatorname{path}_{2}=\operatorname{Gpath}\left(\right.$ Mtree $\left._{2},\{j\}_{c h^{j}=2}\right), \operatorname{path}_{3}=\operatorname{Gpath}\left(\right.$ Mtree $\left._{3},\{j\}_{c h^{j}=3}\right)$.
- $\zeta_{s}^{\text {inter }} \leftarrow \operatorname{Oseeds}\left(\zeta_{s}^{\text {root }},\{j\}_{c h^{j}=2}\right)$.
$-\zeta_{\delta}^{\text {inter }} \leftarrow \operatorname{Oseeds}\left(\zeta_{\delta}^{\text {root }},\{j\}_{c h^{j} \neq 1}\right), \zeta_{u}^{\text {inter }} \leftarrow \operatorname{Oseeds}\left(\zeta_{u}^{\text {root }},\{j\}_{c h^{j}=2}\right)$.
$-\zeta_{\rho_{1}}^{\text {inter }} \leftarrow \operatorname{Oseeds}\left(\zeta_{\rho_{1}}^{\text {root }},\{j\}_{c h^{j} \neq 1}\right), \zeta_{\rho_{2}}^{\text {inter }} \leftarrow \operatorname{Oseeds}\left(\zeta_{\rho_{2}}^{\text {root }},\{j\}_{c h^{j} \neq 2}\right)$.
- For $j$ from 1 to $\kappa$ do

If $c h^{j}=1$ Then
Set $\mathbf{w}_{1}^{j}=\mathbf{u}^{j}+\mathbf{x}$.
$\operatorname{rsp}^{j}=\mathbf{w}_{1}^{j}$.
If $c h^{j}=2$ Then Set $\mathbf{w}_{2}^{j}=\delta^{j}\left(\left(\mathbf{u}^{j}+\mathbf{x}\right) \mathbf{G}_{1}\right)+\mathbf{v}^{j}, \mathbf{w}_{3}^{j}=\operatorname{compress}\left(\delta^{j}(\mathbf{e})\right)$. $b^{j}=b_{I}^{j}, \operatorname{path}^{j}=\operatorname{Gpath}\left(\operatorname{tree}^{j}, I\right)$. $\operatorname{rsp}^{j}=\left(\mathbf{w}_{2}^{j}, \mathbf{w}_{3}^{j}, b^{j}, \operatorname{path}^{j}\right)$.

- Send RSP $=\left(\left\{\operatorname{rsp}^{i}\right\}_{i=1}^{\kappa}\right.$, path $_{1}$, path $\left._{2}, \operatorname{path}_{3}, \zeta_{*}^{\text {inter }}\right)$.

Verification: $\mathcal{V}_{2}^{\text {oom }}\left(\left(\mathbf{G},\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}\right), \mathrm{CMT}, \mathbf{c h}, \operatorname{RSP}, \theta\right)$ :

- $\left\{\zeta_{s}^{j}\right\}_{c h^{j}=2} \leftarrow \operatorname{Recover}\left(\zeta_{s}^{\text {inter }},\{j\}_{c h^{j}=2}\right)$.
$-\left\{\zeta_{\delta}^{j}\right\}_{c h^{j} \neq 1} \leftarrow \operatorname{Recover}\left(\zeta_{\delta}^{\text {inter }},\{j\}_{c h^{j} \neq 1}\right),\left\{\zeta_{u}^{j}\right\}_{c h^{j}=2} \leftarrow \operatorname{Recover}\left(\zeta_{u}^{\text {inter }},\{j\}_{c h^{j}=2}\right)$.
$-\left\{\zeta_{\rho_{1}}^{j}\right\}_{c h^{j} \neq 1} \leftarrow \operatorname{Recover}\left(\zeta_{\rho_{1}}^{\text {inter }},\{j\}_{c h^{j} \neq 1}\right),\left\{\zeta_{\rho_{2}}^{j}\right\}_{c h^{j} \neq 2} \leftarrow \operatorname{Recover}\left(\zeta_{\rho_{2}}^{\text {inter }},\{j\}_{c h^{j} \neq 2}\right)$.
- For $j$ from 1 to $\kappa$ do

If $c h^{j}=1$ Then
$\operatorname{Set}\left(c_{2}^{j}, c_{3}^{j}\right) \leftarrow \mathcal{V}_{2}^{g}\left(c h^{j}, r s p_{j}, \zeta_{\delta^{\prime}}^{j}, \rho_{2}^{j}, \rho_{3}^{j}, \theta\right)$.
If $c h^{j}=2$ Then
Set $\left(c_{1}^{j}, c_{3}^{j}\right) \leftarrow \mathcal{V}_{2}^{g}\left(c h^{j}, \operatorname{rsp}^{j}, \rho_{3}^{j}, \theta\right)$.
If $c h^{j}=3$ Then
Set $\left(c_{1}^{j}, c_{2}^{j}\right) \leftarrow \mathcal{V}_{2}^{g}\left(c h^{j}, \operatorname{rsp}^{j}, \zeta_{s}^{j}, \zeta_{r}^{j}, \zeta_{\delta}^{j}, \rho_{2}^{j}, \theta\right)$.

- $C_{1}=\operatorname{Rebuild}\left(\left\{c_{1}^{j}\right\}_{c h^{j} \neq 1}, \operatorname{path}_{1}\right), C_{2}=\operatorname{Rebuild}\left(\left\{c_{2}^{j}\right\}_{c h^{j} \neq 2}, \operatorname{path}_{2}\right)$,
- $C_{3}=\operatorname{Rebuild}\left(\left\{c_{3}^{j}\right\}_{c h^{j} \neq 3}, \operatorname{path}_{3}\right)$.
- Check if $\mathrm{CMT}=\mathcal{H}\left(C_{1}, C_{2}, C_{3}\right)$. If the above are met, output 1 ; otherwise, output 0 .

Fig. 4. The GSD-based one-out-of-many proof $\Pi^{\text {oom }}=\left(\mathcal{P}^{\text {oom }}=\left(\mathcal{P}_{1}^{\text {oom }}, \mathcal{P}_{2}^{\text {oom }}\right), \mathcal{V}^{\text {oom }}=\right.$ $\left.\left(\mathcal{V}_{1}^{\text {oom }}, \mathcal{V}_{2}^{\text {oom }}\right)\right)$. Let $\zeta_{*}^{\text {inter }}=\left(\zeta_{s}^{\text {inter }}, \zeta_{u}^{\text {inter }}, \zeta_{\delta}^{\text {inter }}, \zeta_{\rho_{1}}^{\text {inter }}, \zeta_{\rho_{2}}^{\text {inter }}\right)$.

For convenience, in later proof we let $\pi^{j}=\pi_{1}^{j}, \mathbf{p}^{j}=\mathbf{p}_{1}^{j}$. $\mathcal{E}$ then checks if $\left.\operatorname{Com}\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j} ; b^{j}\right)\right) \neq \operatorname{leaf}_{i}^{j}$ for $\forall i \in[N]$. If indeed, by employing the Merkle tree extractor in Lemma 1 with input ( $\left.\operatorname{tree}^{j}, \operatorname{Com}\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j} ; b^{j}\right)\right)$, path $)$, it outputs a collision in $\mathcal{H}$. Otherwise, there exists an index $I \in[N]$ satisfying $\operatorname{Com}\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j} ; b^{j}\right)=\operatorname{leaf}_{I}^{j}$ and $\mathcal{E}$ further checks if $\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j}, b^{j}\right) \neq$
$\left(\pi^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}_{1}^{j}+\mathbf{y}_{I}^{j}\right)+\mathbf{p}^{j}, b_{I}^{j}\right)$. If so, $\mathcal{E}$ breaks the binding property of Com. Otherwise, $\mathcal{E}$ gets $\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j}=\pi^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}_{1}+\mathbf{y}_{I}^{j}\right)+\mathbf{p}^{j}$ and $b^{j}=b_{I}^{j}$ and so it deduces that $\left(\mathbf{w}_{1}^{j}-\mathbf{p}_{2}^{j}\right) \mathbf{G}_{1}+\left(\pi^{j}\right)^{-1}\left(\mathbf{w}_{3}^{j}\right)=\mathbf{y}_{I}$ by Eq. (4), where $\left(\pi^{j}\right)^{-1}\left(\mathbf{w}_{3}^{j}\right) \in B(n, t)$. This means that for some $I \in[N], \mathcal{E}$ outputs the witness $\left(\mathbf{w}_{1}^{j}-\mathbf{p}_{2}^{j},\left(\pi^{j}\right)^{-1}\left(\mathbf{w}_{3}^{j}\right)\right)$.

Honest-Verifier Zero-Knowledge: Assume that $\mathcal{A}$ has accessed the oracle $\mathcal{O}^{*}(\cdot)$ a total of $\mathcal{Q}$ times, where $\mathcal{O}^{*}(\cdot)$ instantiates the hash function, algorithm Stree, and Com. Let $E_{i}$ denote the $\mathcal{A}^{\mathcal{O}}\left(\operatorname{Sim}_{i}(s, \mathbf{c h})\right)=1$, for $i=1, \cdots, 6$. Sim is built as follows:

Sim first runs

$$
\left\{\begin{array}{l}
\theta \leftarrow\{0,1\}^{2 \lambda}, \zeta_{\delta}^{\text {inter }} \leftarrow \operatorname{Simseeds}\left(\{j\}_{c h^{j} \neq 1}, \theta\right) ; \\
\zeta_{\rho_{1}}^{\text {inter }} \leftarrow \operatorname{Simseeds}\left(\{j\}_{c h^{j} \neq 1}, \theta\right), \zeta_{\rho_{2}}^{\text {inter }} \leftarrow \operatorname{Simseeds}\left(\{j\}_{c h^{j} \neq 2}, \theta\right) \\
\zeta_{s}^{\text {inter }} \leftarrow \operatorname{Simseeds}\left(\{j\}_{c h^{j}=2}, \theta\right), \zeta_{u}^{\text {inter }} \leftarrow \operatorname{Simseeds}\left(\{j\}_{c h^{j}=2}, \theta\right)
\end{array}\right.
$$

Then, Sim obtains random coins by
$\left\{\begin{array}{l}\left\{\zeta_{\rho_{1}}^{j}\right\}_{c h^{j} \neq 1} \leftarrow \operatorname{Recover}\left(\zeta_{\rho_{1}}^{\text {inter }},\{j\}_{c h^{j} \neq 1}\right) ;\left\{\zeta_{\rho_{2}}^{j}\right\}_{c h^{j} \neq 2} \leftarrow \operatorname{Recover}\left(\zeta_{\rho_{2}}^{\text {inter }},\{j\}_{c h^{j} \neq 2}\right) ; \\ \left\{\zeta_{s}^{j}\right\}_{c h^{j}=2} \leftarrow \operatorname{Recover}\left(\zeta_{s}^{\text {inter }},\{j\}_{c h^{j}=2}\right) ;\left\{\zeta_{u}^{j}\right\}_{c h^{j}=2} \leftarrow \operatorname{Recover}\left(\zeta_{u}^{\text {inter }},\{j\}_{c h^{j}=2}\right) ; \\ \left\{\zeta_{\delta}^{j}\right\}_{c h j \neq 1} \leftarrow \operatorname{Recover}\left(\zeta_{\delta}^{\text {inter }},\{j\}_{c h j \neq 1}\right) .\end{array}\right.$
For $j=1$ to $\kappa:$ Sim performs
Case $c h^{j}=1$ :

1. Sim samples $\mathbf{w}_{1}^{j} \stackrel{\oiint}{\leftarrow} \mathbb{F}_{q}^{k}, c_{1}^{j} \stackrel{\Phi}{\leftarrow}\{0,1\}^{2 \lambda}$ and sets $\mathbf{p}_{1}^{j} \stackrel{\Phi, \xi_{\delta}^{j}}{\leftarrow} \mathbb{F}_{2}^{n}, \pi_{1}^{j} \stackrel{\Phi, \xi_{\delta}^{j}}{\leftrightarrows} \mathcal{S}_{n}$.
2. $\operatorname{Sim}$ sets $c_{2}^{j}=\operatorname{Com}\left(\pi_{1}^{j}, \mathbf{p}_{1}^{j} ; \rho_{2}^{j}\right)$ and $c_{3}^{j}=\operatorname{Com}\left(\pi_{1}^{j}\left(\mathbf{w}_{1}^{j} \mathbf{G}_{1}\right)+\mathbf{p}_{1}^{j} ; \rho_{3}^{j}\right)$.
3. Sim sets rsp ${ }^{j}=\mathbf{w}_{1}^{j}$.

Sim computes CMT $:=\mathcal{H}\left(C_{1}, C_{2}, C_{3}\right)$, where

$$
C_{1} \leftarrow \operatorname{Mtree}\left(c_{1}^{1}, \cdots, c_{1}^{\kappa}\right), C_{2} \leftarrow \operatorname{Mtree}\left(c_{2}^{1}, \cdots, c_{2}^{\kappa}\right), C_{3} \leftarrow \operatorname{Mtree}\left(c_{3}^{1}, \cdots, c_{3}^{\kappa}\right)
$$

and obtains path ${ }_{i}=\operatorname{Gpath}\left(\right.$ Mtree $\left._{i},\{j\}_{c h^{j}=i}\right)$ for $i=1,2,3$. It sets

$$
\mathrm{RSP}=\left(\left\{\operatorname{rsp}^{i}\right\}_{i=1}^{\kappa}, \operatorname{path}_{1}, \operatorname{path}_{2}, \operatorname{path}_{3}, \zeta_{*}^{\text {inter }}\right)
$$

and returns (CMT, ch, RSP, $\theta$ ).
Case $c h^{j}=2$ :

1. Sim chooses the following random objects:

$$
\mathbf{w}_{2}^{j} \stackrel{\oiint}{\leftarrow} \mathbb{F}_{2}^{n}, \mathbf{w}_{3}^{j} \stackrel{\oiint}{\leftarrow} B(n, t), b^{j} \stackrel{\$}{\leftrightarrows}\{0,1\}^{\lambda} ; \text { leaf }_{i}^{j} \stackrel{\oiint}{\leftarrow}\{0,1\}^{2 \lambda}, \forall i \in[2 ; N], c_{2}^{j} \leftrightarrows\{0,1\}^{2 \lambda} .
$$

2. $\operatorname{Sim}$ sets leaf ${ }_{1}^{j}=\operatorname{Com}\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j} ; b^{j}\right)$ and $\left(\right.$ tree $\left.^{j}, \operatorname{root}^{j}\right)=I H-M$ tree $\left(\right.$ leaf $\left.^{j}\right)$.
3. Sim sets $c_{1}^{j}=\operatorname{root}^{j}$ and $c_{3}^{j}=\operatorname{Com}\left(\mathbf{w}_{2}^{j} ; \rho_{3}^{j}\right)$.
4. Sim runs Gpath $\left(\operatorname{tree}^{j}, 1\right)$ to retrieve the path and sets $\operatorname{rsp}^{j}=$ $\left(\mathbf{w}_{2}^{j}, \mathbf{w}_{3}^{j}, b^{j}\right.$, path $\left.^{j}\right)$.

Case $c h^{j}=3$ :

1. Sim samples the following random objects:

$$
\mathbf{p}_{2}^{j} \stackrel{\Phi, \xi_{u}^{j}}{\leftrightarrows} \mathbb{F}_{2}^{k_{1}} ; \mathbf{p}_{3}^{j} \stackrel{\Phi, \xi_{\delta}^{j}}{\leftrightarrows} \mathbb{F}_{2}^{n} ; \pi_{2}^{j} \stackrel{\Phi, \xi_{\delta}^{j}}{\leftrightarrows} \mathcal{S}_{n}, c_{3}^{j} \stackrel{\$}{\leftarrow}\{0,1\}^{2 \lambda}
$$

2. $\operatorname{Sim}$ sets leaf ${ }^{j}=\left(\operatorname{Com}\left(\pi_{2}^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}_{1}+\mathbf{y}_{1}\right)+\mathbf{p}_{3}^{j} ; b_{1}^{j}\right), \cdots, \operatorname{Com}\left(\pi_{2}^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}_{1}+\mathbf{y}_{N}\right)+\right.\right.$ $\left.\left.\mathbf{p}_{3}^{j} ; b_{N}^{j}\right)\right)$ and calculates its $\operatorname{root}^{j}$, where $\left(b_{1}^{j}, \cdots, b_{N}^{j}\right)=\operatorname{Stree}\left(\xi_{s}^{j}, N\right)$.
3. $\operatorname{Sim}$ sets $c_{1}^{j}=\operatorname{root}^{j}$ and $c_{2}^{j}=\operatorname{Com}\left(\pi_{2}^{j}, \mathbf{p}_{3}^{j} ; \rho_{2}^{j}\right)$.

Similar to the proof of Theorem 2, we only need to check the case of RSP. We use a sequence of simulators $\left\{\operatorname{Sim}_{i}\right\}_{i=1}^{6}$ to prove that Sim and an honest prover are indistinguishable, in which $\mathrm{Sim}_{1}$ and Sim $_{6}$ represent the honest prover and Sim, respectively.
$\operatorname{Sim}_{2}$ : The only difference between Sim $_{2}$ and the honest prover is that the tuple internal seeds $\zeta_{*}^{\text {inter }}$ are generated by the algorithm Simseeds with the input ch intead of being generated by the algorithms Stree and Oseeds with inputs $\zeta_{*}^{\text {root }}$ and $\mathbf{c h}$. According to Lemma 3, the advantage of distinguishing between these two tuples internal seeds is $\mathcal{Q} / 2^{\lambda}$ when the oracle $\mathcal{O}^{\text {Stree }}(\cdot)$ is accessed $\mathcal{Q}$ times. Therefore, we have $\left|\operatorname{Pr}\left[E_{2}\right]-\operatorname{Pr}\left[E_{1}\right]\right| \leq \mathcal{Q} / 2^{\lambda}$.

Observe that, if $\zeta_{*}^{\text {inter }}$ has not been queried, when $c h^{j}=1$ and $c h^{j}=3, S i m_{2}$ can perfectly simulate. We only prove the case of $c h^{j}=2$.
$\operatorname{Sim}_{3}$ : The only difference between $\operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ is that $\left\{b_{i}^{j}\right\}_{i=1}^{N}$ are randomly sampled from $\{0,1\}^{\lambda}$ instead of being generated by $\mathcal{O}^{\text {Stree }}(\cdot)$ with the input $\zeta_{s}^{j}$, where $\zeta_{s}^{j}$ is generated by $\mathcal{O}^{\text {Oseeds }}\left(\zeta_{s}^{\text {inter }}\right)$. If $\zeta_{s}^{j}$ has not been queried by $\mathcal{A}$ to the oracle $\mathcal{O}^{\text {Stree }}(\cdot), \operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ are indistinguishable. Thus, if $\mathcal{O}^{\text {Stree }}(\cdot)$ is accessed $\mathcal{Q}$ times and the probability of colliding with $\zeta_{s}^{j}$ each query is $2^{\lambda}$, the probability of colliding with $\zeta_{s}^{j}$ after $\mathcal{Q}$ queries is $\mathcal{Q} / 2^{\lambda}$. Thus, we have $\left|\operatorname{Pr}\left[E_{3}\right]-\operatorname{Pr}\left[E_{2}\right]\right| \leq \mathcal{Q} / 2^{\lambda}$.
$\operatorname{Sim}_{4}$ : The only difference between $\operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ is that $\left\{\operatorname{leaf}_{i}^{j}\right\}_{i=1, i \neq I}^{N}$ are randomly sampled from $\{0,1\}^{2 \lambda}$ instead of being generated by $\mathcal{O}^{\text {Com }}(\cdot)$ with the tuple $\left(\delta^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}+\mathbf{y}_{i}\right)+\mathbf{p}_{3}^{j} ; b_{i}^{j}\right)$ for $i \neq I$. If all tuples have not been queried by $\mathcal{A}$ to $\mathcal{O}^{\mathrm{Com}}(\cdot), \operatorname{Sim}_{3}$ and $\operatorname{Sim}_{2}$ are indistinguishable. Let $\mathcal{Q}_{\text {com }_{i}}$ represent the number of times $\mathcal{O}^{\operatorname{Com}_{i}}(\cdot)$ is accessed. Since the minimum entropy of $b_{i}^{j}$ is $1 / 2^{\lambda}$, the minimum entropy of tuple $\left(\delta^{j}\left(\mathbf{p}_{2}^{j} \mathbf{G}+\mathbf{y}_{i}\right)+\mathbf{p}_{3}^{j} ; b_{i}^{j}\right)$ is at most $1 / 2^{\lambda}$. Hence, the probability of collision with the tuple in each query is at most $1 / 2^{\lambda}$. Furthermore, since $\sum_{i=1}^{N} \mathcal{Q}_{\mathrm{com}_{i}} \leq \mathcal{Q}$, we have $\left|\operatorname{Pr}\left[E_{4}\right]-\operatorname{Pr}\left[E_{3}\right]\right| \leq Q / 2^{\lambda}$.
$\operatorname{Sim}_{5}$ : There are two differences between $\operatorname{Sim}_{5}$ and $\operatorname{Sim}_{4}$. Firstly, $c_{3}^{j}$ is randomly sampled from $\{0,1\}^{2 \lambda}$. Secondly, leaf ${ }_{I}^{j}=\operatorname{Com}\left(\mathbf{w}_{2}^{j}+\mathbf{w}_{3}^{j} ; b_{I}^{j}\right)$, where $\mathbf{w}_{2}^{j}$ and $\mathbf{w}_{3}^{j}$ are randomly sampled from $\mathbb{F}_{2}^{n}$ and $B(n, t)$ respectively. Since $\mathbf{w}_{2}^{j}$ and $\mathbf{w}_{3}^{j}$ follows the random distribution as the real transcript, we have $\operatorname{Pr}\left[E_{5}\right]=\operatorname{Pr}\left[E_{4}\right]$.
$\operatorname{Sim}_{6}$ : The only difference between $\operatorname{Sim}_{6}$ and $\operatorname{Sim}_{5}$ is that 1 is used instead of $I$ in witness. Lemma 2 states that regardless of whether the selected index is 1 or $I$, the root and path follow the same distribution. Therefore, we have $\operatorname{Pr}\left[E_{6}\right]=\operatorname{Pr}\left[E_{5}\right]$.

Thus, we have $\mid \operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\mathcal{P}(s, w\right.$, ch $\left.)) \rightarrow 1\right]-\operatorname{Pr}\left[\mathcal{A}^{\mathcal{O}}(\operatorname{Sim}(s, \mathbf{c h})) \rightarrow 1\right] \left\lvert\, \leq \frac{3 \mathcal{O}}{2^{\lambda}}\right.$.

Communication Cost: (1) The cost of commitments is $2 \lambda(5 \kappa / 6+1)$. (2) The cost of seeds is about $(\kappa / 3)(20 \lambda / 3)+2 \lambda$. (3) The cost of vectors and the path of the Merkle tree is about $(\kappa / 3)\left(\frac{3 n}{2}+k+2 \lambda \log N\right)$.

### 3.3 Our Set-Membership Proof

A set-membership proof is a concept similar to an one-out-of-many proof. It allows one to prove that an element in a public set satisfies a given property, i.e. given a publicly set $\mathcal{I}$ and a property $G$, one proves the existence of an element $\alpha_{i}$ such that $\alpha_{i} \in \mathcal{I}$ and $G\left(\alpha_{i}\right)$ holds. Consider an example where a commitment $\mathbf{c}=\operatorname{Com}_{\mathrm{McE}}$ and a public set $\mathcal{I}=\left\{\alpha_{1}, \cdots, \alpha_{N}\right\}$ are given. The goal is to demonstrate that $\mathbf{c}$ is a commitment to an element in $\mathcal{I}$ and so our set-membership proof can be achieved by the protocol in Fig. 4 with the input of the set $\left[\mathbf{c}_{1}=\mathbf{c}+\operatorname{Com}_{\mathrm{McE}}\left(\alpha_{1} ;(\mathbf{0}, \mathbf{0})\right), \cdots, \mathbf{c}_{N}=\mathbf{c}+\operatorname{Com}_{\mathrm{McE}}\left(\alpha_{N} ;(\mathbf{0}, \mathbf{0})\right)\right]$ and public commitment key $\mathbf{G}$.

## 4 Our Code-Based Logarithmic-Size Ring Signature Scheme

A ring signature enables a ring member to sign a message on behalf of the ring anonymously. Our GSD-based one-out-of-many proof can be transformed into a ring signature scheme through Fiat-Shamir transform. Specifically, each user has a public-private key pair $\left(\mathbf{y}_{i},\left(\mathbf{x}_{i}, \mathbf{e}_{i}\right)\right)$, where $\mathbf{y}_{i}=\mathbf{x}_{i} \mathbf{G}+\mathbf{e}_{i}$ and $\mathbf{e}_{i}$ is small. The signature for a message $\mu$ is our GSD-based one-out-of-many proof for ( $\mathbf{x}_{i}, \mathbf{e}_{i}$ ) satisfying Eq. (3), where $\mu$ is the input of the random oracle in Fiat-Shamir heuristic. Our ring signature scheme is presented in Fig. 5.

```
RS.Setup \(\left(1^{\lambda}\right)\) :
    - \(\mathbf{G} \stackrel{\&}{\leftarrow} \mathbb{F}_{2}^{k \times n}\), where \(n=\mathcal{O}(\lambda)\) and \(k=\mathcal{O}(\lambda)\).
    - \(\mathcal{H}_{\text {com }} \stackrel{\&}{\stackrel{\&}{\leftarrow}} \mathcal{H}\left(1^{\lambda}\right), \mathcal{H}_{F S} \stackrel{\&}{\leftarrow} \mathcal{H}\left(1^{\lambda}, \kappa\right), \mathcal{H}_{\text {Merkle }} \stackrel{\$}{\leftarrow} \mathcal{H}\left(1^{\lambda}, N\right)\), where \(\kappa=\omega(\log (\lambda))\).
    - Return \(p p=\left(\mathbf{G}, \mathcal{H}_{F S}, \mathcal{H}_{c o m}\right)\).
RS.KeGen \((p p, N)\) :
    - \(\mathbf{x} \stackrel{\&}{\leftarrow} \mathbb{F}_{2}^{k}, \mathbf{e} \stackrel{\&}{\leftarrow} B(n, t), \mathbf{y}=\mathbf{x G}+\mathbf{e}\).
    - Return \((p k, s k)=(\mathbf{y},(\mathbf{x}, \mathbf{e}))\).
\(\operatorname{RS} . \operatorname{Sign}\left(s k_{j}, M, R\right)\) :
    - CMT \(\leftarrow \mathcal{P}_{1}^{o o m}\left(\mathbf{G}, R, s k_{j}\right)\).
    - \(\mathbf{c h} \leftarrow \mathcal{H}_{F S}(M, R\), CMT \()\).
    \(-\mathrm{RSP} \leftarrow \mathcal{P}_{2}^{\text {oom }}\left(\mathbf{G}, R, \mathbf{c h}, s k_{j}\right) . \quad\) - Return \(\mathcal{V}_{2}^{\text {oom }}(\mathbf{G}, R,(\mathrm{CMT}, \mathbf{c h}, \mathrm{RSP}))\).
    - Return \(\sigma=\) (CMT, RSP).
```

Fig. 5. Our ring signature scheme. Set $R:=\left(p k_{1}, \cdots, p k_{N}\right)$.
First, we introduce the definition and security requirements of a ring signature scheme.

Definition 1. A ring signature scheme contains four polynomial-time algorithms $\mathcal{R S}=($ RS.Setup, RS.KeyGen, RS.Sign, RS.Verify $)$,
$-p p \leftarrow \mathbf{R S} . \operatorname{Setup}\left(1^{\lambda}\right):$ Taking a security parameter $1^{\lambda}$ as input, output the public parameters pp.
$-(p k, s k) \leftarrow$ RS.KeyGen $(p p, N)$ : Taking the public parameter $p p$ and the number $N$ of ring users as input, publish a pair of public-private keys $\left(p k_{i}, s k_{i}\right)$ for each user $i \in[N]$.
$-\sigma \leftarrow \mathbf{R S} . \operatorname{Sign}\left(R, M\right.$, sk) : Taking the list of public keys $R=\left(p k_{1}, \cdots, p k_{N}\right)$, a private key sk and a message $M$ as input, generate a signature $\sigma$.
$-b \leftarrow \mathbf{R S} . \operatorname{Verify}(R, M, \sigma):$ Taking the list of public keys $R$, a message $M$, and a signature $\sigma$ as input, output $b$ either 1 (accept) or 0 (reject).

A ring signature needs to satisfy three properties: correctness, unforgeability, and anonymity. Correctness ensures that a valid signature can always be verified. Unforgeability guarantees that only users in the ring can generate valid signatures. Anonymity ensures that the output signature does not leak the identity of the signer.

Definition 2 (Correctness). A ring signature scheme achieves correctness if for any $\lambda \in \mathbb{N}, N=$ poly $(\lambda), j \in[N]$ and every message $M$, the following holds:

Definition 3 (Unforgeability w.r.t. insider corruption). A ring signature scheme $\mathcal{R S}=($ RS.Setup, RS.KeyGen, RS.Sign, RS.Verify) is unforgeable if the advantage of $\mathcal{A}$ is negligible in the following game:

1. $p p \leftarrow \mathbf{R S} . \operatorname{Setup}\left(1^{\lambda}\right),\left(p k_{i}, s k_{i}\right) \leftarrow \mathbf{R S} . \operatorname{KeyGen}(p p, N), \forall i \in[N]$;
2. $\mathcal{A}$ can have access to the corrupted oracle $\mathbf{C o}(\cdot)$ with any $p k_{j} \in R$ and $\mathbf{C o}(\cdot)$ returns the $s k_{j}$ to $\mathcal{A}$ and adds $p k_{j}$ to the set $C U$;
3. $\mathcal{A}$ can have access to the RS.Sign( $\cdot$ ) with $\left(p k_{j}, M\right)$ and then RS.Sign $(\cdot)$ returns a signature $\sigma$ using the secret key sk $k_{j}$;
4. $\mathcal{A}$ outputs $\left(R^{*}, M^{*}, \sigma^{*}\right)$ such that RS.Verify $\left(R^{*}, M^{*}, \sigma^{*}\right)=1$, where $\left(R^{*}, M^{*}\right)$ has never been asked and $R^{*} \cap C U=\emptyset$.

The advantage of breaking unforgeability is

$$
\operatorname{Adv}_{\mathcal{A}}^{U n f}(\lambda)=\operatorname{Pr}[\mathbf{R S} . \operatorname{Verify}(R, M, \sigma)=1]
$$

Definition 4 (Anonymity). A ring signature scheme $\mathcal{R S}=$ (RS.Setup, RS.KeyGen, RS.Sign, RS.Verify) is anonymous if the advantage of $\mathcal{A}$ is negligible in the following game:

1. $p p \leftarrow \mathbf{R S} . \operatorname{Setup}\left(1^{\lambda}\right),\left(p k_{i}, s k_{i}\right) \leftarrow \mathbf{R S} . \operatorname{KeyGen}(p p, N), \forall i \in[N] ;$
2. $\mathcal{A}$ selects a tuple $\left(M, p k_{i_{0}}, p k_{i_{1}}\right), i_{0}, i_{1} \in[N]$;
3. $\sigma \leftarrow \mathbf{R S} . \operatorname{Sign}\left(M, s k_{i_{b}}\right), b \stackrel{\$}{\leftarrow}\{0,1\}$;
4. $\mathcal{A}$ returns $a b^{\prime}$.

The advantage of breaking anonymity is

$$
\begin{equation*}
\operatorname{Adv}_{\mathcal{A}}^{\text {Anon }}(\lambda)=\left|\operatorname{Pr}\left[b=b^{\prime}\right]-1 / 2\right| \tag{5}
\end{equation*}
$$

Theorem 4. Our ring signature scheme in Fig. 5 achieves correctness, anonymity and unforgeability with respect to insider corruptions in the random oracle model.

Proof. Correctness: The correctness in Fig. 5 can be directly inferred from the completeness in Fig. 4.

Anonymity: Since our GSD-based one-out-of-many proof is zero-knowledge, it implies that the protocol is witness-indistinguishable. As a result, the anonymity in Fig. 5 can be obtained immediately.
Unforgeability: Without providing specific details we only provide the proof framework as follows. The challenger first selects an index $j^{*}$ and set the $p k_{j^{*}}$ as the challenge instance. The rest $p k_{j}$ are generated as the same as the real
RS.KeGen. If $\mathcal{A}$ queries RS.Sign $(\cdot)$ with $p k_{j^{*}}$, the challenger uses the simulator of Fig. 4 to output the signature. Otherwise, the challenger honestly generates the signature. Under the condition that $j^{*}$ has not been queried with $\mathbf{C o}(\cdot)$ and $\mathcal{A}$ outputs a forged signature about $p k_{j^{*}}$, the challenger is able to extract the solution to the challenge problem via rewind techniques.

## 5 Code-Based Group Signatures

Our GSD-based one-out-of-many proof can be applied in the construction of a group signature. However, unlike ring signatures, a group signature scheme cannot be obtained by directly applying the Fiat-Shamir transform to our one-out-of-many proofs. Therefore, we first construct a ZKAoK that allows a signer to prove both its membership in the group and the honest encryption of its own identity using the public key of the openers. Then, we utilize the Fiat-Shamir transform on the ZKAoK to get our group signature scheme. The overarching concept of this ZKAoK is to combine our GSD-based one-out-of-many proof and our set-memberships proof. We first give the definition and security requirements of a group signature.

Definition 5. A group signature scheme contains five polynomial-time algorithms (GS.Setup, GS.KeyGen, GS.Sign, GS.Verify, GS.Open) in which:
$-(p p, m p k, m s k) \leftarrow \mathbf{G S} . \operatorname{Setup}\left(1^{\lambda}\right):$ Taking a security parameter $\lambda$ as input, output the public parameters pp and the group manager's public-secret key pair ( $m p k, m s k$ ).
$-(p k, s k) \leftarrow$ GS.KeyGen $(p p, N)$ : Taking the public parameter pp and the number $N$ of group members as input, publish a pair of public and private keys $\left(p k_{i}, s k_{i}\right)$ for each user $i, i \in[N]$.
$-\sigma \leftarrow \mathbf{G S . S i g n}(R, m p k, M, s k):$ Taking the list of public keys $R=\left(p k_{1}, \cdots\right.$, $p k_{N}$ ), the manager's public key mpk, a private key sk and a message $M$ as input, generate a signature $\sigma$.
$-b \leftarrow$ GS.Verify $(R, M, \sigma):$ Taking the public key $R$, a message $M$, and a signature $\sigma$ as input, output b either 1 (accept) or 0 (reject).
$-i \leftarrow \mathbf{G S . O p e n}(R, m s k, M, \sigma):$ Taking the public key $R$, the group manager's secret key msk, a message $M$ and a group signature $\sigma$ as input, output an index $i \in[N]$ or $\perp$, indicating failure.

A group signature scheme needs to achieve three requirements: correctness, anonymity and traceability. We give the relaxed anonymity requirement, namely CPA-anonymity.

Definition 6 (Correctness). A group signature scheme is correct if for $\forall \lambda \in$ $\mathbb{N}, N=\operatorname{poly}(\lambda), j \in[N]$ and any message $M$, the following is true:

$$
\operatorname{Pr}\left[\begin{array}{c|c} 
& (p p, m p k, m s k) \leftarrow \mathbf{G S . S e t u p}\left(1^{\lambda}\right), \\
\text { GS.Verify }(R, M, \sigma)=1 & \left(p k_{i}, s k_{i}\right) \leftarrow \mathbf{G S . K e y G e n}(p p), \forall i \in[N], \\
\text { GS.Open }(m s k, R, M, \sigma)=j . & R=\left(p k_{1}, \cdots, p k_{N}\right), \\
& \sigma \leftarrow \mathbf{G S . S i g n}\left(R, m p k, M, s k_{j}\right) .
\end{array}\right]=1 .
$$

Definition 7 (CPA-anonymity). A group signature scheme $\mathcal{G S}=(\mathbf{G S}$. Setup, GS.KeyGen, GS.Sign, GS.Verify, GS.Open) is CPA-anonymous if the advantage of any PPT adversary $\mathcal{A}$ is negligible in the following game:

1. $(p p, m p k, m s k) \leftarrow$ GS.Setup $\left.1^{\lambda}\right)$;
2. $\left(p k_{i}, s k_{i}\right) \leftarrow \operatorname{GS} . \operatorname{KeyGen}(p p, N), \forall i \in[N]$;
3. $\mathcal{A}$ selects a tuple $\left(M, p k_{i_{0}}, p k_{i_{1}}\right), i_{0}, i_{1} \in[N]$;
4. $\sigma \leftarrow \mathbf{G S . S i g n}\left(R, m p k, M, s k_{i_{b}}\right), b \stackrel{\$}{\leftarrow}\{0,1\}$;
5. $\mathcal{A}$ outputs a guess $b^{\prime}$.

The advantage of $\mathcal{A}$ in breaking CPA-anonymity is denoted by

$$
\operatorname{Adv}_{\mathcal{A}}^{A n o n}(\lambda)=\left|\operatorname{Pr}\left[b=b^{\prime}\right]-1 / 2\right|
$$

Definition 8 (Traceability). A group scheme $\mathcal{G S}=$ (GS.Setup, GS., KeyGen, GS.Sign, GS.Verify, GS.Open) is traceable if the advantage of any PPT $\mathcal{A}$ is negligible in the following game:

1. $(p p, m p k, m s k) \leftarrow \mathbf{G S} . \operatorname{Setup}\left(1^{\lambda}\right)$;
2. $\left(p k_{i}, s k_{i}\right) \leftarrow$ GS.KeyGen $(p p, N), \forall i \in[N]$;
3. $\mathcal{A}$ can have access to the corrupted oracle $\mathbf{C o}(\cdot)$ with any $p k_{j} \in R$, and $\mathbf{C o}(\cdot)$ returns the sk $k_{j}$ to $\mathcal{A}$ and adds $p k_{j}$ to the set $C U$;
4. $\mathcal{A}$ can have access to the $\mathbf{G S} . \operatorname{Sign}(\cdot)$ with $\left(p k_{j}, M\right)$ and $\mathbf{G S} . \operatorname{Sign}(\cdot)$ returns a signature $\sigma$ using the secert key $k_{j}$;
5. $\mathcal{A}$ outputs $\left(R^{*}, M^{*}, \sigma^{*}\right)$ such that GS.Verify $\left(R^{*}, M^{*}, \sigma^{*}\right)=1$, where $\left(R^{*}, M^{*}\right)$ have never been asked and $R^{*} \cap C U=\emptyset$.

The advantage of breaking traceability is denoted by

$$
\operatorname{Adv}_{\mathcal{A}}^{T r a c}(\lambda)=\operatorname{Pr}\left[\begin{array}{c}
\mathbf{G S . V e r i f y}\left(R, m p k, M^{*}, \sigma^{*}\right)=1, \\
\mathbf{G S} . O p e n \\
\left(R, m s k, M^{*}, \sigma^{*}\right) \notin C U .
\end{array}\right] .
$$

CPA-McEliece: We review the randomized McEliece encryption scheme [36]. It includes the following three algorithms: $\mathrm{KeyGen}_{\mathrm{McE}}, \mathrm{Enc}_{\mathrm{McE}}$, and $\operatorname{Dec}_{\mathrm{McE}}$.
$-\left(p k=\mathbf{G}_{\mathrm{McE}}, s k=\left(\mathbf{S}, \mathbf{G}^{\prime}, \mathbf{P}\right)\right) \leftarrow \operatorname{KeyGen}_{\mathrm{McE}}\left(1^{\lambda}\right):$ With an integer $\lambda$ as input, select a generator matrix $\mathbf{G}^{\prime}$ of a random $w$-error-correcting ( $m, \ell$ ) code, and sample a random matrix $\mathbf{S} \in \mathbb{F}_{2}^{\ell \times \ell}$ and a random $m$-dimension permutation matrix $\mathbf{P}$, where $m=\mathcal{O}(\lambda), \ell=\mathcal{O}(\lambda), w=\mathcal{O}(\lambda)$. Output the encryption key as $\mathbf{G}_{\mathrm{McE}}=\mathbf{S G}^{\prime} \mathbf{P}$ and the decryption key as $\left(\mathbf{S}, \mathbf{G}^{\prime}, \mathbf{P}\right)$.

- $\mathbf{c t} \leftarrow \operatorname{Enc}_{\mathrm{McE}}\left(\mathbf{G}_{\mathrm{McE}}, \mathbf{m}\right):$ With a plaintext $\mathbf{m} \in\{0,1\}^{\ell_{2}}$ and the $\mathbf{G}_{\mathrm{McE}}$ as input, sample two random vectors $\mathbf{z} \in \mathbb{F}_{2}^{\ell_{1}}$ and $\mathbf{s} \in B(m, w)$, where $\ell=\ell_{1}+\ell_{2}$. Output the ciphertext $\mathbf{c t}=(\mathbf{z} \| \mathbf{m}) \mathbf{G}+\mathbf{s}$.
$-\mathbf{m} \leftarrow \operatorname{Dec}_{\mathrm{McE}}(\mathbf{c t}, s k)$ : With the ciphertext $\mathbf{c t}$ and $s k$ as input, compute $\mathbf{m}^{\prime}=\mathbf{S}^{-1} \mathcal{D}_{\mathbf{G}^{\prime}}\left(\mathbf{c t}^{-1}\right)$, where $\mathcal{D}_{\mathbf{G}^{\prime}}$ is the error-correcting algorithm. Parse the $\mathbf{m}^{\prime}=(\mathbf{z}, \mathbf{m}) \in \mathbb{F}_{2}^{\ell_{1}} \times \mathbb{F}_{2}^{\ell_{2}}$ and outputs $\mathbf{m}$.
The above scheme's CPA-security is based on the following two problems.
Problem 5 (Decisional McEliece problem [36]). Given a matrix $\mathbf{G} \in \mathbb{F}_{2}^{k \times n}$, determine whether it is randomly sampled or generated by the $\operatorname{KeyGen}_{\mathrm{McE}}$.
Problem 6 (Decisional Learning Parity with (fixed-weight) Noise problem [15]). Given a matrix $\mathbf{G} \in \mathbb{F}_{2}^{k \times n}$ and a vector $\mathbf{y} \in \mathbb{F}_{2}^{n}$, determine whether $\mathbf{y}$ is randomly generated or generated by $\mathbf{x G}+\mathbf{e}$, where $\mathbf{x} \in \mathbb{F}_{2}^{k}$ and $\mathbf{e} \in B(n, t)$.


### 5.1 The Underlying Protocol of Our Group Signature

In this subsection, we construct a ZKAoK in Fig. 6 to act as the foundational component of our group signature scheme. We first give an overview of our construction. Let $k, n, \ell=\ell_{1}+\ell_{2}, m$ denote integers, and $\operatorname{bin}(j)$ denote the binary representation of $j$ with length $\ell_{2}$. The public input includes two matrices $\mathbf{G} \in \mathbb{F}_{2}^{k \times n}, \mathbf{G}_{\mathrm{McE}}=\binom{\mathbf{G}_{\mathrm{McE}}^{1}}{\mathbf{G}_{\mathrm{McE}}^{2}} \in \mathbb{F}_{2}^{\ell \times m}$, any vector $\mathbf{y}_{i} \in \mathbb{F}_{2}^{n}, i \in[N]$ and a ciphertext ct $\in \mathbb{F}_{2}^{m}$. The protocol allows one to prove the following relation in zero-knowledge

$$
\begin{align*}
& -\mathbf{x} \mathbf{G}+\mathbf{e}=\mathbf{y}_{I} \wedge \mathbf{x} \in \mathbb{F}_{2}^{k}, \mathbf{e} \in B(n, t)  \tag{6}\\
& -(\mathbf{z} \| \operatorname{bin}(I)) \mathbf{G}_{\mathrm{McE}}+\mathbf{s}=\mathbf{c t} \wedge \mathbf{z} \in \mathbb{F}_{2}^{\ell_{1}}, \mathbf{s} \in B(m, w)  \tag{7}\\
& -I \in[N] \tag{8}
\end{align*}
$$

Round 1: $\mathcal{P}_{1}^{\mathrm{GS}}(\triangle,(I, \mathbf{x}, \mathbf{e}, \mathbf{z}, \mathbf{s}))$ :
$-\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\zeta_{s}, N\right)$.
$-\left\{\operatorname{leaf}_{i}\right\}_{i=1}^{N}=\left\{\operatorname{Com}\left(\delta\left(\mathbf{u G}+\mathbf{y}_{i}\right)+\mathbf{v}, \phi\left((\mathbf{r} \| \operatorname{bin}(i)) \mathbf{G}_{\mathrm{McE}}+\mathbf{c t}\right)+\mathbf{f} ; b_{i}\right)\right\}_{i=1}^{N}$.

- (root, tree) $=\mathrm{IH}$-Mtree(tree).
- Send CMT $:=\left(c_{1}, c_{2}, c_{3}\right)$ to $\mathcal{V}$, where

$$
\left\{\begin{array}{l}
c_{1}=\text { root } ; \\
c_{2}=\operatorname{Com}\left(\delta, \phi, \mathbf{v}, \mathbf{f} ; \rho_{2}\right) ; \\
c_{3}=\operatorname{Com}\left(\delta((\mathbf{u}+\mathbf{x}) \mathbf{G})+\mathbf{v}, \phi\left((\mathbf{r}+\mathbf{z} \| \mathbf{0}) \mathbf{G}_{\mathrm{McE}}\right)+\mathbf{f} ; \rho_{3}\right) .
\end{array}\right.
$$

Round 2: $\mathcal{V}_{1}^{\mathrm{GS}}(\mathrm{CMT})$ sends a challenge $c h \stackrel{\$}{\leftarrow}\{1,2,3\}$ to $\mathcal{P}$.
Round 3: $\mathcal{P}_{2}^{\mathrm{GS}}(\triangle,(I, \mathbf{x}, \mathbf{e}, \mathbf{z}, \mathbf{s}), c h)$ :

- Case $c h=1$ : Set $\xi_{\delta, \phi}^{\prime}=\zeta_{\delta, \phi}, \mathbf{w}_{1}=\mathbf{u}+\mathbf{x}, \mathbf{w}_{2}=\mathbf{r}+\mathbf{z}$.

Send RSP $=\left(\xi_{\delta, \phi}^{\prime}, \mathbf{w}_{1}, \mathbf{w}_{2}, \rho_{2}, \rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=2$ : Set

$$
\left\{\begin{array}{l}
\mathbf{w}_{3}=\delta((\mathbf{u}+\mathbf{x}) \mathbf{G})+\mathbf{v}, \mathbf{w}_{4}=\delta(\mathbf{e}), \mathbf{w}_{5}=\phi\left((\mathbf{r}+\mathbf{z} \| \mathbf{0}) \mathbf{G}_{\mathrm{McE}}\right)+\mathbf{f} ; \\
\mathbf{w}_{6}=\phi(\mathbf{s}), b=b_{I}, \operatorname{path}=\operatorname{Gpath}(\operatorname{tree}, I) .
\end{array}\right.
$$

Send RSP $=\left(\mathbf{w}_{3}, \mathbf{w}_{4}, \mathbf{w}_{5}, \mathbf{w}_{6}, b\right.$, path, $\left.\rho_{3}\right)$ to $\mathcal{V}$.

- Case $c h=3$ : Set $\xi_{s}=\zeta_{s}, \xi_{u, r}=\zeta_{u, r}, \xi_{\delta, \phi}=\zeta_{\delta, \phi}$.

$$
\text { Send RSP }=\left(\xi_{s}, \xi_{u, r}, \xi_{\delta, \phi}, \rho_{2}\right) \text { to } \mathcal{V}
$$

Verification: $\mathcal{V}_{2}^{\mathrm{GS}}(\triangle, \mathrm{CMT}$, ch, RSP $)$ :
 and check if
$c_{2}=\operatorname{Com}\left(\pi_{1}, \pi_{2}, \mathbf{p}_{1}, \mathbf{p}_{2} ; \rho_{2}\right), c_{3}=\operatorname{Com}\left(\pi_{1}\left(\mathbf{w}_{1} \mathbf{G}\right)+\mathbf{p}_{1}, \pi_{2}\left(\mathbf{w}_{2} \mathbf{G}_{\mathrm{McE}}^{1}\right)+\mathbf{p}_{2} ; \rho_{2}\right)$.

- Case $c h=2$ : Compute $\mathrm{R}_{1}$ as Rebuild(path, $\left.\operatorname{Com}\left(\mathbf{w}_{3}+\mathbf{w}_{4}, \mathbf{w}_{5}+\mathbf{w}_{6} ; b\right)\right)$, and check if $\mathbf{w}_{4} \in B(n, t), \mathbf{w}_{6} \in B(m, w)$ and

$$
c_{1}=\mathrm{R}_{1}, c_{3}=\operatorname{Com}\left(\mathbf{w}_{3}, \mathbf{w}_{5} ; \rho_{3}\right)
$$

 $\pi_{4} \stackrel{\Phi_{,}, \xi_{\delta, \phi}}{\leftrightarrows} \mathcal{S}_{m} .\left(b_{1}, \cdots, b_{N}\right)=\operatorname{Stree}\left(\xi_{s}, N\right)$.
$\left\{\operatorname{leaf}_{i}\right\}_{i=1}^{N}=\left\{\operatorname{Com}\left(\pi_{3}\left(\mathbf{p}_{3} \mathbf{G}+\mathbf{y}_{i}\right)+\mathbf{p}_{4}, \pi_{4}\left(\left(\mathbf{p}_{5} \| \operatorname{bin}(i)\right) \mathbf{G}_{\mathrm{McE}}+\mathbf{c t}\right)+\mathbf{p}_{6} ; b_{i}\right)\right\}_{i=1}^{N}$. Obtain $R_{2}$ as IH-Mtree(leaf) and check if

$$
c_{1}=\mathrm{R}_{2}, c_{2}=\operatorname{Com}\left(\pi_{3}, \pi_{4}, \mathbf{p}_{4}, \mathbf{p}_{6} ; \rho_{2}\right) .
$$

$\mathcal{V}$ outputs 1 when all conditions are met, else it outputs 0 .
Fig. 6. The underlying ZKAoK $\Pi^{\mathrm{GS}}=\left(\mathcal{P}^{\mathrm{GS}}=\left(\mathcal{P}_{1}^{\mathrm{GS}}, \mathcal{P}_{2}^{\mathrm{GS}}\right), \mathcal{V}^{\mathrm{GS}}=\left(\mathcal{V}_{1}^{\mathrm{GS}}, \mathcal{V}_{2}^{\mathrm{GS}}\right)\right)$ of our group signature scheme. Use $\triangle$ to denote $\left(\mathbf{G}, \mathbf{G}_{\mathrm{McE}}, \mathbf{y}_{1}, \cdots, \mathbf{y}_{N}, \mathbf{c t}\right)$.

To prove Eqs. (6) and (8), we can utilize our GSD-based one-out-of-many proof with the public input $\left(\mathbf{G},\{\mathbf{y}\}_{i=1}^{N}\right)$. Likewise, to prove Eqs. (7) and (8), we can employ our set-membership proof with the public input $\left(\mathbf{G}_{\mathrm{McE}}, \mathbf{c t}\right)$. To prove Eqs. (6), (7), and (8) simultaneously, we need to merge these two proofs. The overarching concept is to pair the $N+2$ corresponding commitments from the former proof with the $N+2$ commitments from the latter proof in sequential order, and then compress the last $N$ pairs of commitments related to $\left(\left\{\mathbf{y}_{i}\right\}_{i=1}^{N}, \mathbf{c t}\right)$ into a single root using the IH -Mtree. Next, the prover sends the root along with the remaining two pairs to the verifier. The rest steps are similar to the Fig. 4, with the difference being that what needs to be revealed and verified is the commitment pair. The protocol for this relation (6)(7)(8) is in Fig. 6.

Theorem 5. The protocol in Fig. 6 is an argument of knowledge with the perfect completeness and zero-knowledge.

Proof. We only provide the framework of the proof. Completeness: This can be obtained from the correctness of the Merkle tree and seedtree. Soundness: If a adversary can be accepted with a probability greater than $2 / 3$, then we proceed as in Theorem 3. Namely, we construct an extractor to extract ( $I, \mathbf{x}, \mathbf{e}, \mathbf{z}, \mathbf{s}$ ) from three valid responses. Zero-knowledge: Using the similar steps in Theorem 3, we can build a simulator for this protocol.

Communication cost: (1) The cost of commitments is about $2 \lambda(5 \kappa / 6+1)$. (2) The cost of seeds is about $(\kappa / 3)(20 \lambda / 3)+2 \lambda$. (3) The cost of vectors and the path of Merkle tree is about $(\kappa / 3)\left(\frac{3 n}{2}+\frac{3 m}{2}+k+\ell+2 \lambda \log N\right)$.

### 5.2 Our Code-Base Logarithmic-Size Group Signature Scheme

Our group signature scheme is described in Fig. 7, and its correctness can be directly inferred from the completeness in Fig. 6.

The security of our group signature is guaranteed by Theorems 6 and 7. The proofs for these theorems can be found in [27, Section 5.2].

Theorem 6. Our group signature scheme in Fig. 7 is CPA-anonymous based on the hardness of $\operatorname{DMcE}(m, \ell, w)$ and $\operatorname{DLPN}\left(m, \ell_{1}, w\right)$ problems, and the zeroknowledge property of protocol in Fig. 6.

Theorem 7. Our group scheme satisfies full traceability based on the hardness of GSD problem in the random oracle model.

## 6 Concrete Instantiation

We choose parameter sets for our ring signature and group signature schemes under the 128 -bit security level. The parameters are set as follows:

1. The parameters $(n, k, t)$ for GSD problem and the parameters $(m, \ell, w)$ for McEliece encryption scheme are set to achieve the 128-bit security level.
```
GS.Setup \(\left(1^{\lambda}\right)\) :
    - \(\mathbf{G} \leftarrow \mathbb{F}_{2}^{k \times n}\), where \(n=\mathcal{O}(\lambda)\) and \(k=\mathcal{O}(\lambda)\).
    \(-\left(\mathbf{G}_{\mathrm{McE}}, s k_{\mathrm{McE}}\right) \leftarrow \operatorname{KeyGen} \mathrm{McE}\left(1^{\lambda}\right)\), where \(\mathbf{G}_{\mathrm{McE}} \in \mathbb{F}_{2}^{\ell \times m}\).
    - \(\mathcal{H}_{\text {com }} \stackrel{\$}{\leftarrow} \mathcal{H}\left(1^{\lambda}\right), \mathcal{H}_{F S} \stackrel{\$}{\leftarrow} \mathcal{H}\left(1^{\lambda}, \kappa\right), \mathcal{H}_{\text {Merkle }} \stackrel{\$}{\leftarrow} \mathcal{H}\left(1^{\lambda}, N\right)\) where \(\kappa=\omega(\log (\lambda))\).
    - Return \(p p=\left(\mathbf{G}, \mathbf{G}_{\mathrm{McE}}, \mathcal{H}_{F S}, \mathcal{H}_{c o m}\right)\).
GS.KeGen \((p p)\) :
    \(-\mathbf{x} \stackrel{\$}{\leftarrow} \mathbb{F}_{2}^{k}, \mathbf{e} \stackrel{\Phi}{\leftarrow} \mathrm{~B}(n, t), \mathbf{y}=\mathbf{x G}+\mathbf{e}\).
    - Return \((p k, s k)=(\mathbf{y},(\mathbf{x}, \mathbf{e}))\).
\(\operatorname{GS} . \operatorname{Sign}\left(s k_{j}, M, R=\left(p k_{1}, \cdots, p k_{N}\right)\right): \quad \operatorname{GS} . \operatorname{Verify}(R, M, \sigma)\) :
    \(-\mathbf{z} \stackrel{\&}{\leftarrow} \mathbb{F}_{2}^{\ell}, \mathbf{s} \stackrel{\&}{\leftarrow} B(m, w)\).
    - \((\mathbf{c t}, \mathrm{CMT}, \mathrm{RSP}) \leftarrow \sigma\).
    \(-\mathbf{c t}=\operatorname{Enc}_{\mathrm{McE}}(M,(\mathbf{z}, \mathbf{s})) \quad-\mathbf{c h}=\mathcal{H}_{F S}(M, R, \mathrm{CMT}, \mathbf{c t})\).
    \(=(\mathbf{z} \| \operatorname{bin}(j)) \mathbf{G}_{\mathrm{McE}}+\mathbf{s} . \quad-\operatorname{Return} \mathcal{V}_{2}^{\mathrm{GS}}\left(\mathbf{G}, \mathbf{G}_{\mathrm{McE}}, R\right.\),
    - for \(i=1\) to \(\kappa\) :
                                (CMT, ch, RSP), ct).
    \(\mathrm{CMT}_{i} \leftarrow \mathcal{P}_{1}^{\mathrm{GS}}\left(\mathbf{G}, \mathbf{G}_{\mathrm{McE}}, \mathbf{c t}, R, s k_{j}\right)\).
    \(-\mathrm{CMT} \leftarrow\left(\mathrm{CMT}_{1}, \cdots, \mathrm{CMT}_{\kappa}\right)\).
    - ch \(\leftarrow \mathcal{H}_{F S}(M, R\), CMT \() . \quad\) GS.Open \(\left(s k_{\mathrm{McE}}, M, \sigma\right)\) :
    - for \(i=1\) to \(\kappa\) : \(\quad-(\mathbf{c t}, \mathrm{CMT}, \mathrm{RSP}) \leftarrow \sigma\).
    \(\operatorname{RSP}_{i} \leftarrow \mathcal{P}_{2}^{\mathrm{GS}}\left(\mathbf{G}, \mathbf{G}_{\mathrm{McE}}, \mathbf{c t}, R, \mathbf{c h}_{i}, s k_{j}\right)\). - If \(\operatorname{Dec}_{\mathrm{McE}}\left(s k_{\mathrm{McE}}, \mathbf{c t}\right)\) fails,
    - RSP \(\leftarrow\left(\operatorname{RSP}_{1}, \cdots, \operatorname{RSP}_{\kappa}\right)\). return \(\perp\), else return
    - Return \(\sigma=(\mathbf{c t}, \mathrm{CMT}, \mathrm{RSP}) . \quad j \leftarrow \operatorname{Dec}_{\mathrm{McE}}\left(s k_{\mathrm{McE}}, \mathbf{c t}\right)\).
```

Fig. 7. Our group signature scheme.
2. To ensure the one-wayness of the public and private keys, the parameters $(n, k, t, N)$ for GDOOM problem 4 are set to achieve the 128 -bit security level.
3. The repetition number $\kappa$ of the protocols in Fig. 4 and Fig. 6 is set to 220 in order to achieve soundness error $2^{-128}$.
4. We use cSHAKE to instantiate the hash functions in our scheme and the Merkle tree, as well as the pseudorandom number generator in the seedtree [25].
5. The signature size of our ring signature scheme is equal to the proof size in Fig. 4 , i.e. $2 \lambda\left(\frac{5 \kappa}{6}+2\right)+\frac{\kappa}{3}\left(\frac{20 \lambda}{3}+\frac{3 n}{2}+k+2 \lambda \log N\right)$.
6. The signature size of our group signature scheme is equal to the proof size in Fig. 6 plus the size of $\mathbf{c t}$, i.e. $2 \lambda\left(\frac{5 \kappa}{6}+2\right)+\frac{\kappa}{3}\left(\frac{20 \lambda}{3}+\frac{3 n}{2}+k+\frac{3 m}{2}+\ell+2 \lambda \log N\right)+m$.

We set $(n, k, t)=(1280,640,132),(1300,650,135),(1360,680,141)$ for $N=$ $2^{6}, 2^{12}, 2^{21}$, respectively, and $(m, \ell, w)=(3488,2720,64)$ as in [12]. Then, we present the signature sizes of our ring signature scheme and group signature scheme under different $N$ in Table 3 and Table 4.

Table 3. Ring signature sizes for $N$.

| $N$ | (user) PK size | Signature Size |
| :--- | :--- | :--- |
| $2^{6}$ | 0.240 KB | 51 KB |
| $2^{12}$ | 0.247 KB | 65 KB |
| $2^{21}$ | 0.255 KB | 87 KB |

Table 4. Group signature sizes for $N$.

| $N$ | (user) PK size | Signature Size |
| :--- | :--- | :--- |
| $2^{6}$ | 0.240 KB | 112 KB |
| $2^{12}$ | 0.247 KB | 126 KB |
| $2^{21}$ | 0.255 KB | 148 KB |

Acknowledgment. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions that substantially improved the quality of this paper. This research was supported by the National Natural Science Foundation of China under Grant No. 62372446, the National Key Research and Development Program of China under Grant No. 2018YFA0704703 and the Key Research Program of the Chinese Academy of Sciences, Grant No. ZDRW-XX-2022-1.

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