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Privacy-Preserving Accountable Cloud Storage

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Privacy-Preserving Accountable Cloud Storage

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***Abstract*—In cloud storage services, a wide range of sensitive information may be leaked to the host server via the exposure of access pattern albeit data is encrypted. Many security-provable schemes have been proposed to preserve the access pattern privacy; however, they may be vulnerable to attacks towards data integrity or availability from malicious users. This is due to the fact that, preserving access pattern privacy requires data to be frequently re-encrypted and re-positioned at the storage server, which can easily conceal the traces that are needed for accountability support to detect misbehaviors and identify attackers. To address this issue, this paper proposes a scheme that integrates accountability support into hash-based ORAMs. Security analysis shows that the proposed scheme can detect misconduct committed by malicious users and identify the attackers, while preserving the access pattern privacy. Overhead analysis shows that the proposed accountability support incurs only slightly increased storage, communication, and computational overheads.**

I. Introduction

Along with the increasing popularity of cloud-based data sharing, security and privacy concerns also arise. Although encrypting data content has been commonly used for data protection, it alone cannot eliminate the concerns completely. This is because users' data access pattern is not preserved and researchers have found that a wide range of private information could be conveniently revealed by observing the access pattern [1]. To address this issue, more and more efficient designs [2]–[17] have been developed to implement oblivious RAM (ORAM) [18], which was originally proposed for software protection but also is a provable solution to data access pattern preservation.

Though initially designed for single-user scenarios, ORAM has also been applied to multi-user scenarios [14], [19]. However, these systems all assume that the outsourced data is accessible to the data owner and trusted users only; hence, they do not provide any protection against attacks from malicious users on data integrity or availability. Unfortunately, users may not always behave faithfully in practice. Thus, it is highly desirable to introduce accountability support into ORAM to provide privacy-preserving accountable cloud storage services. For example, a company may export its financial records to a cloud storage; while it may want to share the financial data with its stake holders, it is critical to protect the integrity of the data and hold a malicious user accountable if data is altered without authorization.

Many schemes [20], [21] have been proposed to provide accountability support in multi-user storage systems. However, these schemes cannot be readily applied to ORAM because of the following conflicting design goals: *preserving access pattern privacy in ORAM requires data blocks to be frequently re-encrypted and re-positioned at the storage server, which can easily conceal the traces that are needed for accountability support to detect misbehaviors and identify attackers.* In this paper, we propose a unique accountability solution for hash-based ORAMs such as the one proposed in [18]. It is capable of detecting misconduct by malicious users and identifying the attackers, while not interfering with the access pattern preservation mechanism inherent from the underlying ORAM. This goal is achieved via a creative application and integration of two well-known security techniques: *Merkle hash tree* [22] and *group signature* [23], as well as a *delicate design of the data block format*. With our scheme, selected traces of accesses are properly recorded for the purpose of attack detection but without revealing the private information of innocent users that shall be kept confidential to protect their access pattern privacy. We have conducted both security analysis and overhead evaluation for the proposed scheme. Results show that our scheme has achieved the design goals of providing accountability support to ORAM and preservation of data access pattern privacy, at the cost of slightly increased storage, communication, and computational overheads.

The rest of the paper is organized as follows. Section II presents the related work. The system model is described in Section III and the proposed design is elaborated in Section IV. Sections V and VI report the security and overhead analysis. Finally, Section VII concludes the paper.

II. Related Work

Oblivious RAM (ORAM), first proposed by Goldreich and Ostrovsky [18], is a well-known technique to hide a user's access pattern from an outsourced data storage server. In recent years, various schemes [2]–[17] have been proposed to improve the performance of ORAM from both theoretical and practical aspects in terms of communication overhead, storage overhead, and query latency.

While ORAM has become more practical in terms of performance, there are security issues that need to be addressed before ORAM can be deployed in real systems. There are only a few works that address these practical security concerns under the framework of ORAM. For example, in [24], an integrity verification scheme for path ORAM [13] was proposed to ensure data integrity against a malicious server with a Merkle hash tree solution. In another example, the problem of ORAM delegation was studied in [25]. It proposes a scheme with which the data owner can delegate controlled access to third parties for the outsourced dataset, while preserving the access pattern privacy. However, this scheme can only be applied to the square-root ORAM [18], which is inefficient in terms of communication overhead. As a third example, a write-once-read-many ORAM (WORM-ORAM) was proposed in [26], which enables the data owner to offer a read-only data service to third parties. It proposes a zero-knowledge proof based scheme to verify the integrity of the encrypted data

in a write-once-read-many setting. But, it imposes expensive communication and computational overheads over the regular ORAM, which may limit its practical applications.

Different from these existing works, we study user accountability in this paper, which is an important security feature required by most data sharing services. We propose a low-overhead scheme to provide user accountability support to hash-based ORAM schemes [4]–[6], [9], [10], [18] without compromising the access pattern privacy provided by the underlying ORAM.

Private information retrieval (PIR) [27], [28] is another popular technique to preserve user's access pattern. However, PIR protocols work on *read-only* data. In this paper, we consider a system where users can both read and write data.

III. System Model and Design Goals

In this paper, we study a system where the owner of a dataset outsources data to a remote storage server and shares data with multiple users. Based on the access control requirement of the application, the owner may authorize different users with different access privileges. For each data item, we consider three types of access privileges: *no access*, *read-only access*, and *write access*. Moreover, in order to prevent leakage of access pattern privacy, the owner is assumed to follow a hash-based Oblivious RAM (ORAM) design to deploy the data on the storage server.

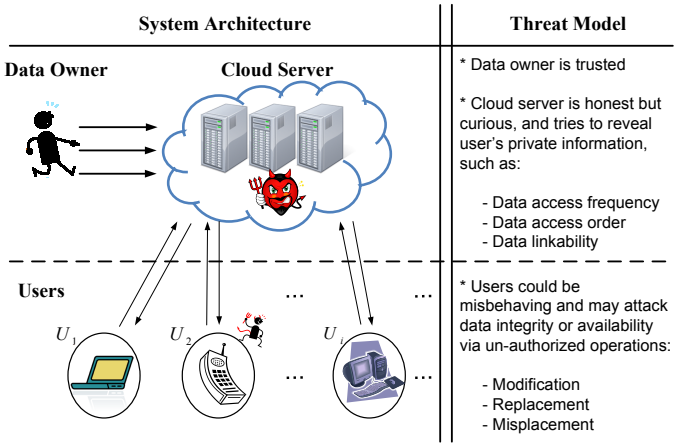


Fig. 1. System architecture and threat model.

There are many possible security or privacy attacks against such multi-user cloud storage systems. As the starting point toward building a fully accountable and privacy-preserving cloud storage system, we assume the following threat model in this paper, as illustrated in Fig. III.

- Data owner is trusted.
- Storage server is honest but curious in learning about data owner and users' data access patterns.
- A user may attempt to attack the data integrity or availability via un-authorized modification, replacement, or misplacement. However, we assume the user executes the underlying ORAM protocol honestly to protect its own access pattern privacy.
- Multiple malicious users may collude. However, more sophisticated collusive attacks launched by the storage server and malicious users together are not considered in this work.
- We do not consider protecting a user's access pattern privacy against a malicious user. Generally, this can be addressed by protecting the communication between the user and the server with TLS [29].

To summarize, the design goals of the proposed scheme are: (i) preserving data owner and users' access patterns to the dataset, including both the overall access pattern and a single user's or a group of users' access pattern; and (ii) detecting data integrity attacks launched by malicious users and, upon detection, enabling data owner to identify the attackers.

IV. Proposed Scheme

Our scheme is designed to integrate with most hash-based ORAM schemes [4]–[6], [9], [10], [18]. Please refer to Appendix 1 for a brief explanation of the ORAM operations. In this paper, we explain how our scheme works with the seminal hash-based ORAM scheme proposed by O. Goldreich and R. Ostrovsky [18], which provides a framework for all other hash-based ORAMs. Our scheme is based on integration of two well-known techniques: (i) *Merkle hash tree* [22] which allows efficient verification of the integrity of a large set of data, and (ii) *group signature* [23] which allows each member of a group to anonymously sign a message on behalf of the group. Please also refer to Appendix 1 for detailed explanations of these techniques. In the following, we first present the intuitions of the proposed scheme, and then explain the details of the design.

A. Scheme Overview: The Intuitions

Built on top of a hash-based ORAM such as [18], our proposed scheme has the ultimate goal of user accountability and data access pattern preservation, which is attained through accomplishing each of the following more specific subgoals:

(G1) If the content of a data block is modified by an un-authorized user, such a modification attack shall be detected and the attacker shall be identified.
(G2) During a query or shuffling process, the set of data blocks that a user uploads to the server shall be the same as the set downloaded earlier. If a user fails to do so by replacing some of the data blocks with others, such a replacement attack shall be detected and the user shall be identified.
(G3) When being uploaded, data blocks shall be placed properly to the buckets decided by the underlying ORAM; that is, the position of each data block shall be determined by a designated hash function. If a user fails to do so, such a misplacement attack shall be detected and the user shall be identified.

Accomplishment of Subgoal (G1) In our scheme, subgoal (G1) is accomplished via group signatures. Initially, when exporting a data block to the server, the data owner generates two group signatures: s – a group signature for the entire data block (on behalf of all the users in the system), and g – a group signature for the content and ID of the data block only (on behalf of the users who have the write privilege to the

data block). When a user accesses a data block, it verifies both signatures. If s is valid but g is invalid, it is detected that the user who last accessed the data block has modified the data block without proper authorization, and the identity of the attacking user can be traced out by the data owner based on the group signature s. If both signatures are valid, the user proceeds to access the data and generates a new group signature s before uploading the data block back to the server. Note that, if the user has the write privilege and has modified the data content, it also needs to generate a new group signature g for the updated data content. At the server side, after it receives a data block from the user, it simply checks the group signature s. If it is invalid, the uploading user is detected to have committed a misconduct.

Accomplishment of Subgoal (G2) During a query or shuffling process, data blocks are re-encrypted and re-arranged. Therefore, it is challenging to ensure that the user always uploads the same set of data blocks that it downloaded from the server. In our scheme, this is accomplished via group signatures and Merkle hash tree. Specifically, after a user requests and downloads a set of data blocks, the server constructs a Merkle hash tree using the hash values of the IDs of the requested blocks as leaf nodes, and calculates the root hash of the tree. Then, the server informs the user of the root hash as well as the co-path information in the Merkle hash tree for each data block. After access to the data, the user updates the following information in each data block before uploading it back to the server: c – hash of the block ID with a new random nonce, e – root hash of the Merkle hash tree (informed by the server), and e' – an encryption of the co-path information (also informed by the server) with a new random nonce. Recall that the data content and block ID are protected by the group signature g.

This way, if a user fails to upload the same set of data blocks back to the server (by replacing some of the data blocks with others), such a replacement attack can be detected by the server or the user who next accesses the data block. For example, if a user replaces the content of a data block with that of another data block, together with block ID, or co-path information, or root hash, or a combination (but not all) of them, this can be detected by the user who next accesses the data block, since the root hash carried in the data block would be different from the one calculated using the block ID and co-path information. However, if the user replaces the entire data block, this can be detected by the server, since either the root hash of the data block is different from all other uploaded blocks, or the encrypted co-path information of the data block is identical to another uploaded block. Also note that the server cannot identify a data block using the hash of the block ID or the co-path information, because both hash and encryption operations use a new random nonce.

Accomplishment of Subgoal (G3) With the above solutions to subgoals (G1) and (G2) in place, the solution to subgoal (G3) becomes straightforward as follows. To ensure that a data block is placed properly according to the underlying ORAM, our scheme requires the user to include the position information (i.e., layer and bucket) as part of the block before generating the group signature s. Next time when another user accesses the block, it checks (i) whether the block was placed at the position specified in the data block, and (ii) whether the position is consistent with the output of the hash function designated by the underlying ORAM.

Next, we elaborate the details of the our scheme which integrates the above solutions to subgoals (G1)-(G3).

B. System Initialization

System initialization is conducted by the owner of the dataset. It consists of four operations: *selection of system parameters*, *user authorization*, *preparation of data blocks*, and *uploading of data blocks to the storage server*. In the following, we describe these operations in detail. Particularly, when describing how to prepare and upload data blocks, the data format and storage structure will also be introduced.

1) Selection of System Parameters: As the first step of system initialization, the data owner classifies all data blocks into *read groups* and *write groups* according to the access policy. Specifically,

- a read group (denoted by R_j) is defined as the j^{th} set of data blocks that have the same read access policy, i.e., they can be read by the same set of users;
- a write group (denoted by W_j) is defined as the j^{th} set of data blocks that have the same write access policy, i.e., they can be written by the same set of users.

Each data block in the system belongs to exactly one read group and one write group. Let n be the total number of data blocks exported to the storage server. Let m_R and m_W denote the number of read groups and write groups, respectively. We have $m_R \leqslant n$ and $m_W \leqslant n$, where the equality holds when every data block has a different read/write access policy. In practice, we usually have $m_R \ll n$ and $m_W \ll n$. Table I lists the system parameters.

TABLE I. SYSTEM PARAMETERS SELECTED BY THE DATA OWNER.

Notation	Description
R_j (W_j)	the j^{th} read (write) group
$m_R (m_W)$	number of read (write) groups
$\mathcal{U}$	the set of all data users
$\mathcal{U}_{R_j}$	the set of users that can read blocks in R_j
$\mathcal{U}_{W_j}$	the set of users that can write blocks in W_j
k	a system symmetric key for all users
k_{R_j} ($j \geq 1$)	a symmetric key that is used to encrypt the plain-text content of all blocks in R_j
$K^+_{W_j}$ ($j \geq 1$)	the group public key for write block group W_j
K^-_{u,W_j} ($j \geq 1$)	a group private key assigned to user u who can write all data blocks in W_j
G_j-$Sig_u(\cdot)$	group signature signed using K^-_{u,W_j}
K^+_0	the group public key for all data blocks
$K^-_{u,0}$	a group private key assigned to user $u \in \mathcal{U}$
G_0-$Sig_u(\cdot)$	group signature signed using $K^-_{u,0}$
$h_l(x, y)$	hash function that maps x and $y \in \{1, \cdots, n\}$ to an integer in $\{1, \cdots, 2^l\}$ ($l = 1, \cdots, \log n$)
$H(\cdot)$	a general one-way hash function
$E_\theta(\cdot)$	a block cipher algorithm with key θ

Let $\mathcal{U}$ denote the set of all users in the system. For each R_j ($j \geq 1$), the data owner selects a symmetric key k_{R_j} to encrypt the plain-text content of all data blocks in R_j. For each W_j ($j \geq 1$), the owner also selects one group public key ($K^+_{W_j}$) and a set of group private keys ($\{K^-_{u,W_j}\}_{u \in \mathcal{U}}$), where K^-_{u,W_j} denotes the private key assigned to user u. We

use G_j-$Sig_u(\cdot)$ to denote the group signature generated with K^-_{u,W_j}. In addition, the data owner also selects the following system parameters:

- k: a system symmetric key for general encryption purposes. It is known to all users in $\mathcal{U}$.
- K^+_0, $\{K^-_{u,0}\}_{u\in\mathcal{U}}$: one group public key ($K^+_0$) and a set of group private keys ($\{K^-_{u,0}\}_{u\in\mathcal{U}}$), where $K^-_{u,0}$ denotes the private key assigned to user u. We use G_0-$Sig_u(\cdot)$ to denote the group signature generated with $K^-_{u,0}$.
- $h_l(x,y)$ for $l = 1, \cdots, \log n$: a set of hash functions, where each $h_l(x,y)$ hashes a pair of positive integers x and $y \in \{1, \cdots, n\}$ to an integer in $\{1, \cdots, 2^l\}$. They are known to all users in $\mathcal{U}$.
- $H(x)$: a hash function that randomly maps one or a sequence of integers to an L-bit integer, where L is a security parameter.
- $E_\theta(\alpha, \beta)$: a symmetric block cipher algorithm working in CBC mode, where θ is the encryption key, α is the initialization vector, and β is the plain-text to be encrypted. We also use $E_\theta(\alpha, \beta, \gamma)$ to denote the encryption of the concatenation of β and γ with the initialization vector α (i.e., the first parameter is always the initialization vector).

2) User Authorization: Among the parameters, K^+_0 and hash function $H(x)$ are available to the public. For each user $u \in \mathcal{U}$, the owner provides the symmetric key k, a distinct group private key $K^-_{u,0}$, and the set of group public keys $K^+_{W_j}$. Let $\mathcal{U}_{R_j}$ and $\mathcal{U}_{W_j}$ denote the set of users who can read blocks in R_j and the set of users who can write blocks in W_j, respectively. If a user u is authorized to read data blocks in R_j, i.e., $u \in \mathcal{U}_{R_j}$, the owner provides the symmetric key k_{R_j} to the user; if a user u is authorized to write data blocks in W_j, i.e., $u \in \mathcal{U}_{W_j}$, the owner provides a group private key K^-_{u,W_j} to the user.

Table II summarizes how the keys are distributed to the server and users. Basically, a user needs to store (i) k, K^+_0, and one group private key $K^-_{u,0}$ ($O(1)$ overhead), (ii) a number of k_{R_j} for the read groups that it is allowed to read ($O(m_R)$ overhead), (iii) a number of group private keys K^-_{u,W_j} for the write groups that it is allowed to write ($O(m_W)$ overhead), (iv) m_W group public keys $K^+_{W_j}$ ($O(m_W)$ overhead). If a misbehaving user is identified, the user could be revoked from the system with existing schemes such as [30], [31].

TABLE II. DISTRIBUTION OF KEYS TO THE SERVER AND USERS.

	k	K^+_0	$K^-_{u,0}$	k_{R_j}	$K^+_{W_j}$	K^-_{u,W_j}
server		√				
$u \in \mathcal{U}$	√	√	√		√	
$u \in \mathcal{U}_{R_j}$	√	√	√	√	√	
$u \in \mathcal{U}_{W_j}$	√	√	√		√	√

3) Preparation of Data Blocks: We use i to denote the ID of a data block and use D_{i,t_i} to denote the data block associated with ID i and time stamp t_i. To simplify the presentation, when describing a data block, we use k_i to denote the encryption key and use K^+_i and $K^-_{u,i}$ to denote the group public key and private keys that are used by data block D_{i,t_i}. For example, if $D_{i,t_i} \in R_{j'}$ and $D_{i,t_i} \in W_{j''}$, we denote $k_i = k_{R_{j'}}$, $K^+_i = K^+_{W_{j''}}$, and $K^-_{u,i} = K^-_{u,W_{j''}}$.

The plain-text content carried in D_{i,t_i} is denoted as w_{i,v_i}, where v_i denotes the version number of the data content and is incremented when the content is updated. To enforce the access control policy, w_{i,v_i} is encrypted together with its ID i by its corresponding encryption key k_i. We use d_{i,v_i} to denote the encrypted data content in D_{i,t_i}, i.e.,

$$d_{i,v_i} = E_{k_i}(r_{i,v_i}, i, w_{i,v_i}). \quad (1)$$

where r_{i,v_i} is a random initialization vector chosen upon each encryption of w_{i,v_i}. Overall, a data block D_{i,t_i} has the following format:

$$D_{i,t_i} = \langle d'_{i,t_i}, c_{i,t_i}, e_{i,t_i-1}, e'_{i,t_i-1}, l_{i,t_i}, b_{i,t_i}, s_{i,t_i} \rangle, \quad (2)$$

where the fields are explained below. A high-level explanation of the purpose of each data field is shown in Fig. 2, while detailed explanations about how these data fields are used will be presented in Section IV-C and Section V.

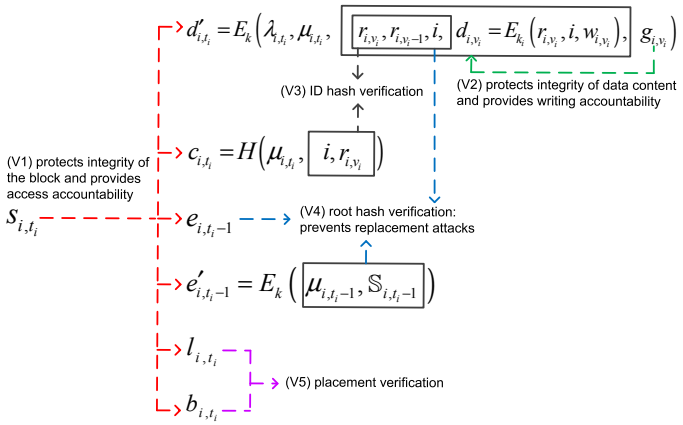


Fig. 2. A high-level explanation of the purpose of each data field in the data block. (V1)-(V5) along the dashed lines indicate the verification steps that are performed by a user, which will be explained later in Section IV-C.

As shown in Fig. 2, d'_{i,t_i} is a one-time encryption of the concatenation of the following items: (i) a random nonce μ_{i,t_i} that is randomly selected upon each encryption, (ii) the random nonce r_{i,v_i} that is used in the encryption of d_{i,v_i}, (iii) the random nonce r_{i,v_i-1} that was used in the encryption of d_{i,v_i-1}, i.e., the previous version of the data content, (iv) the block ID i, (v) the encrypted data content d_{i,v_i}, and (vi) a group signature g_{i,v_i} generated by the owner or a user who has the privilege to write this block, i.e.,

$$g_{i,v_i} = G_i\text{-}Sig_u(i, d_{i,v_i}, r_{i,v_i}, r_{i,v_i-1}). \quad (3)$$

Thus, d'_{i,t_i} has the following format:

$$d'_{i,t_i} = E_k(\lambda_{i,t_i}, \mu_{i,t_i}, r_{i,v_i}, r_{i,v_i-1}, i, d_{i,v_i}, g_{i,v_i}), \quad (4)$$

where λ_{i,t_i} is a random initialization vector that is different from r_{i,v_i} in Eq. (1) and Eq. (3). λ_{i,t_i} can be updated by any user who possesses k and its main purpose is to change the appearance of the encrypted data after each access. In comparison, r_{i,v_i} can only be updated by a user who is authorized to write the data block and its main purpose is to prevent replacement attacks launched by malicious users. We

include another random nonce μ_{i,t_i} because it will be used as the initialization vector for another data field e'_{i,t_i-1}, which will be explained in the following. The purpose of the group signature g_{i,v_i} is to protect the integrity of d'_{i,t_i}, so that only a user who is authorized to write the data block (and hence owns the group private key $K^-_{u,i}$) can update r_{i,v_i}, r_{i,v_i-1}, and d_{i,v_i} legitimately. Meanwhile, it also enables the data owner to track the identity of the user who made the last modification.

c_{i,t_i} is a one-time hash of the block ID i, together with random nonces μ_{i,t_i} and r_{i,v_i}:

$$c_{i,t_i} = H(\mu_{i,t_i}, i, r_{i,v_i}). \quad (5)$$

During each query or reshuffling process, c_{i,t_i} is used by the server to build a Merkle hash tree based on the data blocks requested.

e_{i,t_i-1} is the root hash of the Merkle hash tree that was constructed by the server when D_{i,t_i} was last accessed (for simplicity, we use $t_i - 1$ to denote the time stamp when D_{i,t_i} was last accessed). In other words, the leaf nodes of the Merkle hash tree are the ID hashes of all the blocks downloaded together with D_{i,t_i-1}. The purpose of e_{i,t_i-1} (together with e'_{i,t_i-1} which is explained below) is to let the user and the server collaboratively verify that, when a data block was previously accessed, the set of data blocks uploaded back to the server after the access was the same as the set downloaded.

e'_{i,t_i-1} is a one-time encryption of the hash tree information that is needed to calculate the root hash e_{i,t_i-1}. Specifically,

$$e'_{i,t_i-1} = E_k(\mu_{i,t_i-1}, \mathbb{S}_{i,t_i-1}), \quad (6)$$

where $\mathbb{S}_{i,t_i-1}$ denotes the co-path hash values for leaf hash c_{i,t_i-1} on the Merkle hash tree when the data block was retrieved at time t_i-1. Note that the same initialization vector μ_{i,t_i-1} is used in the encryption of e'_{i,t_i-1} and d'_{i,t_i-1}.

l_{i,t_i} and b_{i,t_i} are the layer and bucket of block D_{i,t_i} in the storage hierarchy respectively. s_{i,t_i} is a group signature of the entire block generated by the owner or any user in the system:

$$s_{i,t_i} = G_0\text{-}Sig_u(d'_{i,t_i}, c_{i,t_i}, e_{i,t_i-1}, e'_{i,t_i-1}, l_{i,t_i}, b_{i,t_i}). \quad (7)$$

Similar to g_{i,v_i}, the purpose of s_{i,t_i} is to allow the server and users to verify the integrity of the entire data block, as well as to enable the owner to track the identity of the user who last accessed the data block.

Initially, the time stamp t_i and the version number v_i are set to 0, both e_{i,t_i-1} and e'_{i,t_i-1} are set to empty, l_{i,t_i} is set to $\log n$, and b_{i,t_i} is set to $h_{\log n}(0, i)$.

4) Uploading of Data Blocks to the Storage Server: All the data blocks are stored to a hierarchy of layers according to the underlying ORAM. Specifically, the hierarchy consists of $\log n$ layers. Each layer l ($1 \leqslant l \leqslant \log n$) includes 2^l buckets and each bucket contains $\log n$ blocks. Hence, the server stores $(2n-2)\log n$ data blocks in total, which includes n *real* data blocks that contain meaningful data exported by the owner. The other $(2n-2)\log n - n$ data blocks in the hierarchy are called *dummy* data blocks. They simply contain random stuffing data and no user (except the owner) is authorized to write a dummy block. To create a dummy data block, the owner randomly generates a unique block ID and some data content, and then creates the data block in the same format as the real data block. Each dummy data block D_{j,t_j} is initialized with t_j set to 0, e_{j,t_j-1} and e'_{j,t_j-1} set to empty, and l_{j,t_j} and b_{j,t_j} set to some layer and bucket so that dummy data blocks fill up all the storage locations not occupied by real data blocks. In addition, the server maintains a counter C_q (with an initial value of 0) which keeps track of the number of queries that have been processed.

C. Query Process

The query process is executed when a user needs to retrieve a target data block (denote its ID as T). We show the flowchart of the proposed query process in Fig. 3(b), together with the flowchart of the query process in the original ORAM in Fig. 3(a). Specifically, to retrieve the target block, a user performs the following operations.

(Q1) Both buckets at the top layer of the storage hierarchy are retrieved from the server. If the target data block is found in the buckets, the flag `found` is set to `true`; else, it is set to `false`.

(Q2) Counter C_q is retrieved from the server and is incremented by 1,

(Q3) For each layer i from 2 to $\log n$, the following is performed:
- If `found` = `true`, a bucket is selected uniformly at random from the layer and all the data blocks in the bucket are retrieved.
- If `found` = `false`, all data blocks in bucket $h_i(\lfloor C_q/2^i \rfloor, T)$ are retrieved. If target block is found among the retrieved blocks, `found` is set to `true`.

(Q4) After all the requested data blocks have been retrieved, the server constructs a Merkle hash tree based on the data ID hashes (i.e., c_{i,t_i}) of the retrieved blocks, calculates the root hash (i.e., e_{i,t_i}) of the tree, and saves it for future verification purposes. Then, the server notifies the user of the root hash and the co-path hash values (i.e., $\mathbb{S}_{i,t_i}$) for each retrieved data block D_{i,t_i}.

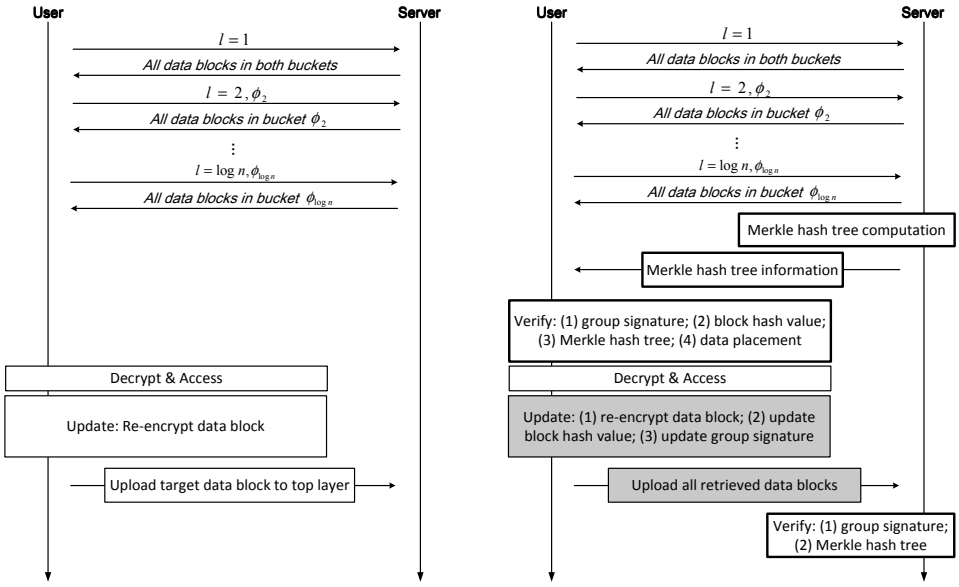
(Q5) The user verifies all the retrieved data blocks, accesses the content of the target data block, re-formats all the retrieved data blocks, and then uploads them back to the server. More specifically, this step involves the operations of *verification*, *updating*, and *uploading*, as explained below.

1) Verification: Each retrieved data block D_{i,t_i} is verified as follows.

(V1) *Verification of group signature s_{i,t_i}:* s_{i,t_i} is verified with the public key K_0^+.

(V2) *Verification of group signature g_{i,v_i}:* g_{i,v_i} is verified with the group public key K_i^+. If it is invalid, a user misconduct has been detected, as the user who last accessed the block must have altered the data content without proper authorization.

(V3) *Verification of ID hash c_{i,t_i}:* The correctness of c_{i,t_i} is verified by checking whether it is equal to $H(\mu_{i,t_i}, i, r_{i,v_i})$. Note that, μ_{i,t_i}, i, and r_{i,v_i} are parts of d'_{i,t_i} and hence protected by the group signature g_{i,v_i}. If c_{i,t_i} is incorrect, a user misconduct has been detected.



(a) original ORAM (b) the proposed scheme

Fig. 3. Flowcharts of the query process in the original ORAM and the proposed scheme. Operations added in the proposed scheme are shown in bold boxes. Operations modified from those in the original ORAM are shown in gray boxes.

(V4) *Verification of root hash* e_{i,t_i-1}*:* Recall that e_{i,t_i-1} is the root hash of the Merkle hash tree constructed by the server when the data block was last accessed. To verify it, the user needs the following information: the ID hash c_{i,t_i-1} and the co-path hashes $\mathbb{S}_{i,t_i-1}$ when the data block was last accessed. As we will explain in the "Updating" operation below, if the last access to the data block was a write access, a new random nonce r_{v_i} would be generated. Therefore, as the user is unsure about the last access, it verifies e_{i,t_i-1} against both r_{v_i} and r_{v_i-1}. In other words, it checks whether e_{i,t_i-1} is the same as the root hash calculated based on using either $H(\mu_{i,t_i-1}, i, r_{i,v_i})$ or $H(\mu_{i,t_i-1}, i, r_{i,v_i-1})$ as the ID hash c_{i,t_i-1}, and the co-path hashes $\mathbb{S}_{i,t_i-1}$. If both fail, a user misconduct has been detected. Note that r_{i,v_i} and r_{i,v_i-1} can be obtained from d'_{i,t_i}, while μ_{i,t_i-1} and $\mathbb{S}_{i,t_i-1}$ can be obtained from e'_{i,t_i-1}.

(V5) *Verification of data block placement:* Suppose D_{i,t_i} is retrieved from bucket b of layer l ($l > 1$). It is checked whether $l_{i,t_i} = l$ and $b_{i,t_i} = b$. Also, if the block is not a dummy, it is verified whether $b = h_l(\lfloor C_q/2^l \rfloor, i)$. If verification fails, a misplacement attack has been detected.

2) Updating: If all the verifications succeed, the user accesses the target data and then updates all the retrieved data blocks as follows.

For each data block i, a new random initialization vector $\lambda_{i,\text{new}}$ and a new random nonce $\mu_{i,\text{new}}$ are selected. Then, the user sets $\lambda_{i,t_i+1} = \lambda_{i,\text{new}}$ and $\mu_{i,t_i+1} = \mu_{i,\text{new}}$. In addition, if a data block is the target block and the current access is a write access, a new random nonce $r_{i,\text{new}}$ is selected and $r_{i,v_i+1} = r_{i,\text{new}}$. Then, for each block, the user calculates d' and c with the updated data content and random nonces. e' and e are updated based on the co-path hashes ($\mathbb{S}$) and the root hash (e) of the Merkle hash tree, which were notified by the server during query step (Q4).

Next, according to the underlying ORAM, a dummy block is randomly picked from the top layer of the storage hierarchy, and the target block swaps its position with the dummy by swapping the values of their b and l fields. For all other blocks, b and l fields remain unchanged. Finally, a new group signature s is generated for each block.

3) Uploading: After all the retrieved data blocks have been updated, they are uploaded back to the server at the positions determined by their b and l values. The order in which the blocks are uploaded is arbitrary. In addition, if the counter C_q is a multiple of 2^l for certain $l \in \{1, \cdots, \log n\}$ but not a multiple of any $2^{l'}$ where $l' > l$, a shuffling process for layer l should be conducted. The shuffling process is elaborated in Section IV-D.

4) Server Operations: Upon receiving an uploaded data block, the server performs the following verifications. If any of them fails, a user misconduct has been detected and the server refuses to accept the block.

(O1) Verify the validity of the group signature s;
(O2) Verify that the root hash e carried in the block is the same as the root hash of the Merkle hash tree constructed by the server during query Step (Q4);
(O3) Verify that the e' value carried in the block is different from all other uploaded blocks. This is to prevent replacement attacks launched by the user.
(O4) Increase the counter C_q by one.

D. Shuffling Process

The shuffling process for layer l is to obliviously reposition and re-format all the blocks residing at layers 1, $\cdots$, l so that: (i) after the shuffling, each bucket contains the same number (i.e., $\log n$) of blocks; (ii) each *real* data block D_{i,t_i} is placed to bucket $h_l(\frac{C_q}{2^l}, i)$ of layer l, where C_q is the afore-mentioned counter keeping track of the number of queries that have been processed. As in the original ORAM,

our proposed shuffling process also contains several rounds of scanning, tagging, and oblivious sorting. However, the original ORAM shuffling scheme must be modified in order to provide accountability support. Due to space limitation, please refer to Appendix 2 for details.

E. Insertion and Deletion

Occasionally, the file system may be updated by adding new data blocks and/or removing existing data blocks. Due to space limitation, please refer to Appendix 3 for how the proposed scheme handles data insertion and deletion.

V. Security Analysis

In this section, we present the security analysis of the proposed scheme.

A. Access Pattern Privacy

We first show that the proposed scheme ensures the same access pattern privacy offered by the underlying ORAM, which is formally presented in Theorem 1. In order to prove Theorem 1, we first present the following two lemmas (Lemma 1 and Lemma 2).

Lemma 1: Compared with the original ORAM, the proposed data format does not provide extra information that helps the server identify a data block.

Proof: To hide access pattern, ORAM requires that the server cannot identify a data block from its appearance when multiple data blocks are put back to the server during a query or shuffling process. To achieve this, each data block in the original ORAM, in its simplest format, is just ciphertext generated over the real data content by a probabilistic symmetric encryption algorithm. In our proposed scheme, as shown in Eq. (2), each data block contains seven data fields that are visible to the server, including d'_{i,t_i}, c_{i,t_i}, e_{i,t_i-1}, e'_{i,t_i-1}, l_{i,t_i}, b_{i,t_i}, and s_{i,t_i}. We now show that, compared with the original ORAM, none of them leaks extra information that may help the server identify a data block.

- d'_{i,t_i}, which contains the real data content, is equivalent to the encrypted data block as in the original ORAM. It is a ciphertext output by a probabilistic encryption function $E(\cdot)$ which is semantically secure. Given that (i) the size of the real content in each data block (i.e., w_{i,v_i}) is the same, and (ii) μ_{i,t_i}, r_{i,v_i}, r_{i,v_i-1}, i, and g_{i,v_i} for each block have the same size, d'_{i,t_i} of each data block has the same length. As a result, compared with the original ORAM, the server does not gain extra information from d'_{i,t_i}.
- c_{i,t_i} is the hash of the concatenation of μ_{i,t_i}, i and r_{i,v_i}. Because μ_{i,t_i} is picked randomly for each data block downloaded during a query or shuffling process, c_{i,t_i} appears random for each uploaded data block. Therefore, the server does not gain extra information from c_{i,t_i}.
- e_{i,t_i-1} is the root hash of a Merkle hash tree that is constructed during a query or shuffling process. In the proposed scheme, data blocks that are put back to the server in the same query or shuffling process will have the same e_{i,t_i-1}. As a result, e_{i,t_i-1} cannot help the server identify a data block.
- e'_{i,t_i-1} is the ciphertext of μ_{i,t_i-1} and $\mathbb{S}_{i,t_i-1}$ with a semantically secure function $E(\cdot)$. Because μ_{i,t_i-1} is randomly picked for each data block, the server does not gain extra information from e'_{i,t_i-1}.
- l_{i,t_i} and b_{i,t_i} are the location information of each data block, which actually are observable by the server. Therefore, inclusion of them in a data block does not leak extra information to the server.
- s_{i,t_i} is a group signature re-generated for each uploaded data block and is random because the content to be signed has changed. Thus, it does not help the server identify a data block.

■

Lemma 2: Compared with the original ORAM, neither the query process nor the shuffling process in the proposed scheme leaks additional information that helps the server identify a data block.

Proof: As for query, in our proposed scheme, the bucket to be retrieved on each layer during downloading is the same as the original ORAM. As explained in the proof of Lemma 1, the Merkle tree construction (i.e., the computation of e_{i,t_i-1} during downloading) and the server verification of the Merkle tree root (during uploading) do not provide the server any additional information to identify a data block. The user verification and update processes all happen at the client side. In the uploading process, the target data block swaps its location with a random dummy block at the top layer. But, because every uploaded data block is updated, the server cannot do better in identifying the target data block than random guessing. Lastly, due to the randomness of group signature generation (i.e., s_{i,t_i}), the server cannot identify a data block by the verification of the group signature. As a result, the query process does not leak additional information.

As for shuffling, similar to query, the Merkle tree construction, the server-side verification, and the client-side verification do not leak additional information. On the other hand, from the algorithm, it is straightforward to see that sorting is oblivious. Therefore, the shuffling process also does not leak additional information. ■

Theorem 1: The proposed scheme provides the same level of access pattern privacy as the underlying ORAM.

Proof: Because neither the modified data format nor the data query/shuffling process downgrades the security of the scheme in term of access pattern privacy, Theorem 1 is a straightforward conclusion from Lemma 1 and Lemma 2. ■

B. User Accountability

We now show that any un-authorized modification, replacement, or misplacement conducted by a malicious user can be detected either by the server or by the user who next accesses the data block.

1) Modification Attacks: Modification attacks are referred to as the attacks where a malicious user modifies the actual content of a data block without proper authorization. This can be detected thanks to the presence of group signature g, which can be signed only by the users who are authorized to write the data block. The identity of the user who last accessed the data block can be identified by opening the group signature s.

2) Replacement Attacks: Instead of modifying the data content, a malicious user may launch replacement attacks by replacing some or all fields of a data block D_{i,t_i} with those of another block D_{j,t_j} or an older version of the same block D_{i,t'_i} ($t'_i < t_i$), and then generating a valid group signature s. Our scheme deals with this type of attacks via Merkle hash tree and consistency checking between fields.

Recall that each data block consists of the following fields: d', c, e, e', l, b, and s. Among these fields, the server keeps a copy of the root hash e and checks whether e in the uploaded block is the same as the saved value. Hence, e is well-protected and cannot be replaced. Also, note that d' and c contain the same random nonce r_{i,v_i}; hence, if one is replaced while the other is not, this can be easily detected by checking the consistency between them. Moreover, attacks against the position information l and b are referred to as *misplacement attacks* and will be discussed later. Therefore, in this section, we analyze the following replacement attacks: *replacement of d' and c*; or *replacement of d', c, and e'*.

a) Replacement of d' and c: This can be detected by the user who next accesses the block during the *root hash verification step (V4)*. As described in (V4), to verify the root hash e_{i,t_i-1} carried in D_{i,t_i}, which was calculated by the server when the block was last accessed, the following information are needed: c_{i,t_i-1} – the ID hash, and $\mathbb{S}_{i,t_i-1}$ – the co-path hashes. c_{i,t_i-1} can be derived as $c_{i,t_i-1} = H(\mu_{i,t_i-1}, i, r_{i,v_i})$, where v_i is the version number of the data content when the block was last accessed, and both i and r_{i,v_i} are embedded in d'_{i,t_i}. Clearly, replacement of d'_{i,t_i} with d'_{j,t_j} of another block would result in an incorrect ID being used to derive c_{i,t_i-1} and hence would fail the verification process. Now, let's consider the attacks by replacing d'_{i,t_i} with an older version of the same block, i.e., d'_{i,t'_i} whose data content has an earlier version number of $v'_i < v_i$. As the nonces embedded in d'_{i,t'_i} are r_{i,v'_i} and r_{i,v'_i-1}, we have $v_i > v'_i > v'_i - 1$. This means that the random nonce r_{i,v_i} needed to derive c_{i,t_i-1} cannot be found in the replaced d', which also would result in a verification failure. Here, we assume that the space for the random nonce is large enough so that the probability of two randomly picked nonces being the same is negligibly small.

b) Replacement of d', c, and e': As described in the *server operation step (O3)*, the server verifies that the e' values are distinct in all the uploaded data blocks during the same query/shuffling process. Therefore, it may only be possible that a malicious user attempts to replace d'_{i,t_i}, c_{i,t_i}, and e'_{i,t_i-1} with those of another block D_{j,t'_j} from a different query/shuffling process, or an older version of the same block D_{i,t'_i} ($t'_i < t_i$). In either case, a different Merkle hash tree was constructed. Therefore, similar to the discussions above, such an attack can be detected by the user who next accesses the block, as it would result in a root hash verification failure due to the replaced co-path hashes. Here, we assume that the hash function H is well designed so that for two different Merkle hash trees, the probability that they have the same root hash is negligibly small.

3) Misplacement Attacks: A malicious user may place a data block in the wrong bucket and/or layer of the storage hierarchy. Such attacks can be detected in one of the following ways: (i) the position of the block is inconsistent with the hash of its ID using the designated hash function; or (ii) the data block cannot be found at the specified position. In the latter case, the server may work with the dataset owner to scan the storage hierarchy to locate the misplaced block and identify the attacker through group signature s.

VI. Overhead Analysis

A. Storage and Communication Overhead

1) Server Storage Overhead: As our scheme requires additional fields in each data block D_{i,t_i}, including μ_{i,t_i}, r_{i,v_i}, r_{i,v_i-1}, i, g_{i,v_i}, c_{i,t_i}, e_{i,t_i-1}, e'_{i,t_i-1}, l_{i,t_i}, b_{i,t_i} and s_{i,t_i}, extra storage is needed on the server. We assume that each hash value (μ_{i,t_i}, r_{i,v_i}, r_{i,v_i-1}, c_{i,t_i}, and e_{i,t_i-1}) is 32-byte long and one group signature (g_{i,v_i} and s_{i,t_i}) takes less than 200 bytes [31]. i is the block ID, which is of $\log n$ bits. l_{i,t_i} and b_{i,t_i} store the layer and bucket indices. Since there are $\log n$ layers in the storage hierarchy and at most n buckets at each layer, l_{i,t_i} is of $\log\log n$ bits and b_{i,t_i} is of $\log n$ bits. e'_{i,t_i-1} introduces a larger overhead, because it stores the information that corresponds to a path from root to leaf in the Merkle hash tree. In the worst case, the Merkle hash tree may contain $n \log n$ data blocks (i.e., when the entire database is shuffled) and thus e'_{i,t_i-1} may store up to $\log(n \log n)$ hash values. Fortunately, this is still considered a small amount of storage overhead in practice. For example, assuming $n \leq 2^{32}$ and each hash value is of 32 bytes, the size of e'_{i,t_i-1} is $32 \log(n \log n)$ bytes, which is less than 1.1 KB, when $n \leq 2^{32}$. To summarize, the overall extra overhead per data block is $O(\log n)$ bytes. Table III shows the storage overhead with different numbers of data blocks. Considering that a data block is typically 64 KB or 256 KB in practice [12], the extra overhead is less than 3% of data block size.

TABLE III. Storage overhead per data block.

# blocks (n)	2^{20}	2^{24}	2^{28}	2^{32}
Extra Overhead	1.32 KB	1.45 KB	1.58 KB	1.71 KB

2) User Storage Overhead: A user also needs an extra storage space to store (i) the encryption keys for the blocks that the user is authorized to read, (ii) the group private keys for the blocks that the user is authorized to write, and (iii) all the group public keys for verifying each block. As a result, a user needs $O(m_R + m_W)$ storage overhead, where m_R and m_W are the number of read groups and number of write groups respectively. Note that in the worst case, the owner may classify each data block as a read/write group, which results in $m_R = m_W = n$, where n is the number of blocks in the system. However, in practice, a shared data set typically may have a limited number of access policies (e.g., no more than a few hundred). Thus, the overhead for storing the keys is acceptable (e.g., no more than a few megabytes). Moreover, as explained in Section IV-C, the Merkle hash tree is constructed by the server and the user only needs to verify the Merkle hash tree information it retrieves; hence, no storage overhead is introduced for this process.

3) Communication Overhead: As explained in the storage overhead, the proposed scheme will increase the data block size slightly. On the other hand, the number of data blocks transmitted during query and shuffling are asymptotically the same between the proposed scheme and the original ORAM. As a result, the proposed scheme adds only small communication overhead to the original ORAM.

B. Computational Overhead

1) Server Overhead: For each data query, the additional (amortized) computational overhead at the server side includes $O(\log^2 n)$ hash computations (to construct a Merkle hash tree) and $O(\log^2 n)$ group signature verifications.

2) User Overhead: For each data block D_{i,t_i} retrieved in a query or shuffling process, a user needs to perform the following extra computations: (i) verification of the group signatures g_{i,v_i} in the retrieved data block (and generation of g_{i,v_i+1} for the updated data block for a write operation); (ii) verification of c_{i,t_i} in the retrieved data block and generation of c_{i,t_i+1} for the updated data block, both of which are hash computations; (iii) decryption of e'_{i,t_i-1} and re-encryption of e'_{i,t_i}; (iv) verification of the root hash e_{i,t_i-1} of the Merkle hash tree, which is composed of a sequence of hash computations; (v) verification of placement of D_{i,t_i}, which is one hash computation; (vi) verification of group signature s_{i,t_i} and generation of s_{i,t_i+1}; and (vii) verification of e_{i,t_i} and $\mathbb{S}_{i,t_i}$ received from the server, which is composed of a sequence of hash computations. Using a modern pairing-based cryptography library such as PBC library [32], each of the above computations can be done efficiently from several milliseconds to several hundreds of milliseconds.

VII. Conclusions and Future Work

This paper proposes an accountability solution for hash-based ORAM schemes such as [18]. It detects misconduct committed by malicious users and identify the attacker, without interfering with the access pattern preservation mechanisms inherent from the underlying ORAM. This is achieved through an integration of Merkle hash tree and group signature techniques, as well as a delicate design of the data block format. As a tradeoff, the storage, communication, and computational overheads are increased slightly. Our proposed accountability support can also be extended to work with other hash-based hierarchical ORAM schemes [4]–[6], [9], [10], as long as the extended data format does not give the server non-negligible advantages in inferring users' access pattern in the integrated schemes. However, its integration with Bloom filter-based or index-based ORAM schemes [2], [3], [7], [8], [11]–[17] is nontrivial, and will be studied in our future work.

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APPENDIX 1

In this section, we explain the three building blocks of our proposed scheme: *Oblivious RAM*, *group signature*, and *Merkle hash tree*.

Oblivious RAM

Existing ORAM schemes can be roughly classified into two categories depending on how the user decides the storage location of a data block: (i) hash-based ORAMs where a data block's storage location is decided according to hash functions, and (ii) index-based ORAMs where a block's storage location is retrieved from an index map. Our scheme is designed to integrate with most hash-based ORAM schemes. In this paper, we present how our scheme works with the seminal hash-based ORAM scheme proposed in [18], which provides a framework for all other hash-based ORAMs. We now briefly explain how this ORAM scheme works:

Storage: In ORAM, user's data are stored as a set of encrypted and equal-sized data blocks, as shown in Fig. 4. All data blocks are organized in a hierarchical structure which consists of $\log n$ layers (where n is the number of data blocks). Layer i contains 2^i buckets, each of which can store $\log n$ data blocks. Layer i may store up to 2^i real data blocks, while the rest are dummy blocks. Real data blocks are stored into buckets based on the hash of their IDs.

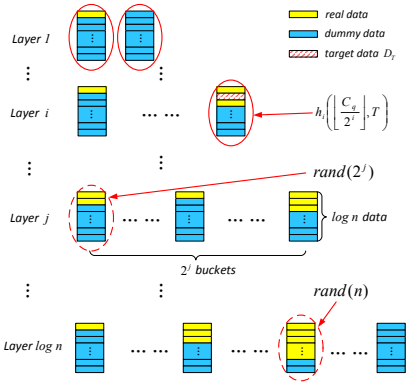

Fig. 4. ORAM storage and the query process for data block D_T. In this example, buckets with circles are selected by the user and all blocks inside those buckets will be downloaded. Solid-line circles denote the buckets selected via applying hash function on target data ID T, and dashed-line circles represent the buckets randomly selected.

Query: The data query is executed whenever the user wants to retrieve a target block from the server. To hide the actual target block from the server, the ORAM query works in a manner so that all layers will be accessed, and the buckets accessed at each layer appear random to the server. Specifically, to retrieve a target block with ID T at the C_q'th query, the user performs the following operations.

- Both buckets at the top layer are retrieved from the server. If the target data block is found in either bucket, the flag `found` is set to `true`; else, it is set to `false`.
- For each layer i from 2 to $\log n$,
  - If `found` = `true`, a bucket is selected uniformly at random from the layer and all data blocks in this bucket are retrieved.
  - If `found` = `false`, all data blocks in bucket $h_i(\lfloor C_q/2^i \rfloor, T)$ are retrieved, where $h_i(\cdot)$ is a hash function for layer i. If the target block is found among the retrieved blocks, `found` is set to `true`.
- At the end of the query, the user randomly selects a dummy data block from the top layer and replaces it with the target data block. Then, all data blocks of the top layer are re-encrypted and uploaded back to the top layer.

3) Shuffling: As target blocks are gradually moved from bottom layers to upper layers, the shuffling process is triggered periodically to avoid layer overflow. For layer i, the shuffling process takes place every 2^i accesses. The shuffling process for layer i essentially re-positions all real data blocks on and above layer i into layer $i+1$ in an oblivious manner. Due to space limitation, please refer to [18] for details.

Group Signature and Merkle Hash Tree

Group signatures [23] are often used to allow each member of a group to anonymously sign a message on behalf of the group. Typically, there is a group manager who is in charge of the membership management and has the ability to reveal the identity of the signer in the event of disputes. For simplicity, we assume that a group signature scheme provides a primitive $G_i\text{-}Sig_u(m)$ which generates the signature for message m with the secret key of group member u, where we use subscript i to differentiate different groups.

A Merkle hash tree [22] is typically used to allow efficient verification of the integrity of a large set of data. In a Merkle hash tree, the leaves are hashes of data blocks and each interior node (including the root) is the hash of its child nodes. The root of a Merkle hash tree is called the *root hash*, and the set of hash values that are needed to calculate the root hash from a leaf node is called the *co-path* (denoted as $\mathbb{S}$) from the leaf node to the root. For example, in Fig. 5, the co-path for data block D_1 from the leaf node h_{0-1} to the root h_{2-1} is $\mathbb{S}_1 = \{h_{0-2}, h_{1-2}\}$.

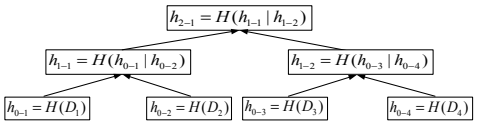

Fig. 5. A Merkle hash tree for verifying the integrity of data blocks D_1-D_4 (H is a hash function).

APPENDIX 2

The shuffling process in the proposed scheme works in the same fashion as in the original ORAM, which contains several rounds of tagging and oblivious sorting. However, because we do not allow a user to add new data blocks to the server, the original ORAM shuffling process must be modified to suit this requirement. In addition, the proposed scheme also requires the server to construct the Merkle hash tree for all the data blocks to be shuffled at the beginning and verify the Merkle hash tree information in each data block when they are finally put back to the server. The user that performs the shuffling also needs to perform various verifications as described in the query process

when data blocks are downloaded. Incorporating accountability mechanisms, the detailed operations of the shuffling process are as follows. An example where $l = 2$ is shown in Fig. 6.

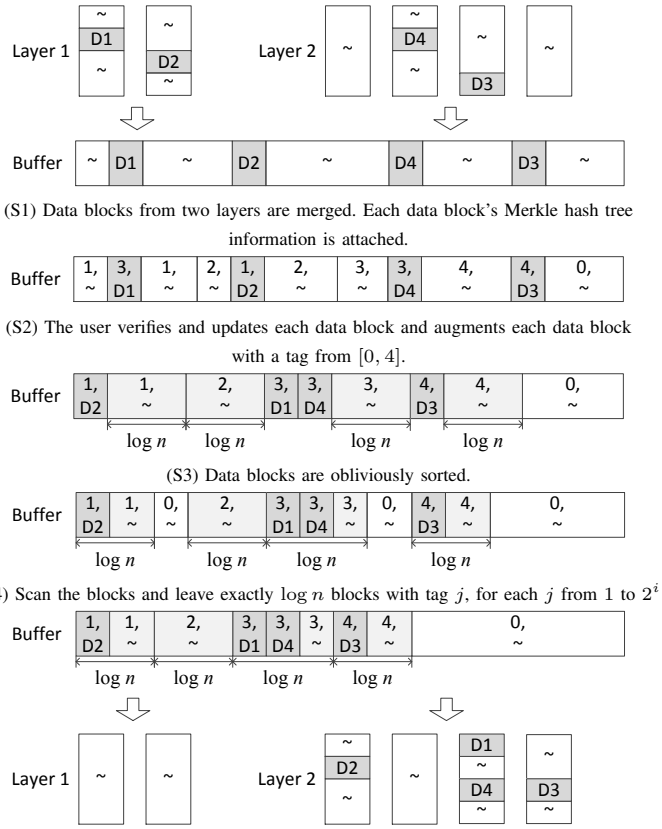

Fig. 6. Example of the shuffling process. Each bucket has $\log n$ data blocks. We use symbol "$\sim$" to represent one or more adjacent dummy data blocks.

(S1) The server merges all the data blocks at layers $1, \cdots, l$ to a *shuffling buffer*, builds a Merkle hash tree with the data ID hash fields of these blocks as leaf nodes, and calculates the root hash. Then, for each block D_{i,t_i} in the buffer, the root hash value e_{i,t_i} and its corresponding co-path values $\mathbb{S}_{i,t_i}$ are attached to the block. After this, the following five steps are performed by the user who conducts the shuffling process.

(S2) In this step, the user scans (i.e., downloads, processes, and re-uploads back) the blocks in the shuffling buffer, one by one. More specifically, after a block D_{i,t_i} has been downloaded, the validity of the data block, including the attached e_{i,t_i} and $\mathbb{S}_{i,t_i}$, is first checked in a similar manner as in the verification process during a regular query (please refer to Section IV-C). If the check fails, the user stops the shuffling process and informs the owner of the potential tampering of the data block. Otherwise, the block is further processed as follows to obtain a new block of different appearance: (i) A new initialization vector $\lambda_{i,\text{new}}$ and a new nonce $\mu_{i,\text{new}}$ are picked uniformly at random. (ii) d'_{i,t_i} is re-computed as $E_k(\lambda_{i,\text{new}},\ \mu_{i,\text{new}},\ r_{i,v_i},\ r_{i,v_i-1},\ i,\ d_{i,v_i},\ g_{i,v_i})$ and c_{i,t_i} is re-computed as $H(\mu_{i,\text{new}}, i, r_{i,v_i})$. (iii) The root hash value is replaced with e_{i,t_i}. (iv) e'_{i,t_i} is computed as $E_k(\mu_{i,t_i}, \mathbb{S}_{i,t_i})$. (v) A tag T_i is assigned to indicate which bucket the block should reside after the shuffling. Particularly, if the block is a real data block of ID i, $T_i = h_l(C_q/2^l, i)$; otherwise (i.e., the block is a dummy block), T_i is picked from $\{0, \cdots, 2^i\}$ such that, after the assignment has been performed for all the dummy blocks in the buffer, $\log n$ dummy blocks are assigned with tag j for each $j = 1, \cdots, 2^i$ while the rest dummy blocks are assigned with tag 0. (vi) Tag T_i is encrypted and saved in field b_i; that is, $b_{i,\text{new}} = E_k(r_{i,t_i+1}, T_i)$. And $l_{i,\text{new}}$ are all set to l. (vii) Group signature s_i is re-computed for the entire block.

(S3) In this step, the user conducts an oblivious sorting for all the blocks in the shuffling buffer, based on the tags carried by the blocks. As a result, the blocks are placed in the shuffling buffer according to the ascending order of their tags, and for blocks of the same tag, the real data blocks are placed before dummy blocks. Note that during the sorting process, the overall data block will be encrypted by the encryption key k to prevent the server from identifying a data block. For more details about how oblivious sorting is performed, please refer to [18].

(S4) Again, the user scans the blocks in the shuffling buffer, one by one. This time, the tags of some dummy blocks are adjusted to ensure that, for each $j = 1, \cdots, 2^l$, exactly $\log n$ (real or dummy) data blocks are assigned with tag j, while other dummy blocks are assigned with tag 0. Based on the sorting result of (S3), the tag adjustment can be conducted as follows by using a temporary counter: For each $j = 1, \cdots, 2^l$, when the first block with tag j is scanned, the counter is initialized to 1. Later on, when a block of the same tag is scanned, the tag of the block remains unchanged and the counter is incremented by 1, if the counter is smaller than $\log n$; otherwise (i.e., the counter is equal to $\log n$), the block should be re-tagged with 0.

(S5) In this step, the user conducts another oblivious sorting for all the blocks in the shuffling buffer, based on the tags carried by the blocks. As a result, the blocks are placed in the shuffling buffer according to the ascending order of their tags; for blocks of the same tag, however, the data blocks are placed randomly.

(S6) In this step, a third scan is performed to specify the new location of each block in the shuffling buffer. Specifically, according to the order produced by (S5), the blocks are placed into the buckets from layer 1 to layer l and from bucket 1 to bucket 2^j for each layer j. Also, for each block i, the $l_{i,\text{new}}$ and $b_{i,\text{new}}$ fields save its assigned layer number and bucket number; e' contains an encrypted version of its $\mathbb{S}_{i,t_i}$ (without a random nonce) to allow the server to check whether the block carries a unique e' value.

Note that, in the last time when all data blocks are uploaded back to buckets, the server needs to check whether the uploaded set is the same as the downloaded set.

APPENDIX 3

Occasionally, the file system may be updated by adding new data blocks and/or removing existing data blocks. In the proposed scheme, data addition and deletion is handled by the data owner and is processed in the same fashion as in the underlying ORAM scheme.

To delete a data block, the owner first creates a new dummy data block (as described in Section IV-B) whose ID is set to be the same as the block to be removed. This new dummy data block will replace the data block to be removed. To achieve this, the data owner makes a query (as described in Section IV-C) with the target set as the data block to be removed. Then when uploading the data blocks back to the server, the owner replaces the target data block with the new dummy data block. Note that due to the Merkle hash tree verification, the new dummy data block's ID must be the same as the ID of the deleted data block, because the root hash is calculated using the removed data block's ID information. Also note that only the data owner can write a dummy data block.

To insert a new data block, the owner first determines if the new block falls into an existing read (write) group. If it doesn't belong to any existing read groups, a new read group R_x is created and the owner selects an encryption key k_{R_x} for this read group. Similarly, if it doesn't belong to any existing write groups, a new write group W_y is created and the owner selects a group public key $K^+_{W_y}$ and a set of group private keys $\{K^-_{u,W_y}\}$ for this write group. Then, the owner (i) publishes $K^+_{W_y}$, (ii) disseminates k_{R_y} to users who can read the new data block, and (iii) disseminates a unique K^-_{u,W_y} to each user who can write the new data block. After that, the owner creates the new data block as described in Section IV-B. In order to put the new data block onto the server, the data owner swaps it with a dummy data block on the server whose ID will be assigned to the new data block. This swapping process is similar to the one described in the last paragraph.

Note that in ORAM, under certain conditions, addition/deletion of a real data block may change the number of layers in the ORAM storage. In such cases, the owner may first change the number of layers per the rules defined in the underlying ORAM scheme and then add/delete the data block as afore-explained.