Enabling Efficient, Secure and Privacy-Preserving Mobile Cloud Storage

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Abstract—Mobile cloud storage (MCS) provides clients with convenient cloud storage service. In this article, we propose an efficient, secure and privacy-preserving mobile cloud storage scheme, which protects the data confidentiality and privacy simultaneously, especially the access pattern. Specifically, we propose an oblivious selection and update (OSU) protocol as the underlying primitive of the proposed mobile cloud storage scheme. OSU is based on onion additively homomorphic encryption with constant encryption layers and enables the client to obliviously retrieve an encrypted data item from the cloud and update it with a fresh value by generating a small encrypted vector, which significantly reduces the client's computation as well as the communication overheads. Compared with previous works, our presented work has valuable properties, such as fine-grained data structure (small item size), lightweight client-side computation (a few of additively homomorphic operations) and constant communication overhead, which make it more suitable for MCS scenario. Moreover, by employing the "verification chunks" method, our scheme can be verifiable to resist malicious cloud. The comparison and evaluation indicate that our scheme is more efficient than existing oblivious storage solutions with the aspects of client and cloud workloads, respectively.

Index Terms—Mobile cloud storage, data security, privacy-preserving, efficient, malicious cloud server

1 Introduction

In MOBILE cloud storage (MCS), data is stored in a cloud and can be accessed from anywhere with mobile devices. Due to the attractive properties, MCS is becoming more and more popular. Some large companies provide MCS services for business purposes, i.e., Apple iCloud, Dropbox, Microsoft OneDrive and Google Drive.

In many situations, the cloud is not considered fully trusted. Thus, the client may employ encryption schemes to keep data confidential before uploading it to the cloud. However, in MSC-based applications, data always be related to certain information, such as location information in location based services. In this situation, which item of data is being accessed leaks addition information to the cloud server. By utilizing this leaked information of access pattern, the cloud may infer the operations of the client and even the contents of the encrypted data. For example, in a searchable encryption system, a cloud can identify approximately 80 percent of the search queries by applying a general inference attack with access pattern leakage and minimal background knowledge [1]. Oblivious technology, such as oblivious transfer (OT) [2], oblivious storage (OS) [3] and oblivious random access machine (ORAM) [4], is a kind of technologies that can protect both data and *access pattern*. Generally speaking, these technologies allow a client to access its outsourced data stored in an untrusted cloud without revealing which items have been visited or even what kinds of operations are requested. Due to the high-level privacy preservation, these technologies have been widely applied in various application scenarios such as searchable encryption [5], [6], [7], encrypted hidden volumes [8], [9], cloud storage [10], [11], [12], [13], multi-party computation [14], [15], [16], [17], [18], etc.

However, there are some challenges to employ existing oblivious schemes into MCS scenario due to several reasons. First, mobile devices are generally connected to the Internet via wireless networks, such as ad-hoc, LTE, and Wi-Fi. That means mobile devices have limited communication bandwidth to download and upload data. Thus, some schemes suffered by the well-known communication bandwidth overhead lower bound result $O(\log N)$ [4] can not be employed into MCS due to the heavy communication overhead.[1] Second, although modern mobile devices, such as mobile phones and tablets, have significantly improvement in terms of computing capability, they still cannot compete with personal computers or other powerful devices to carry heavy computations. Complicated computation also reduces the battery life of mobile devices. Therefore, some schemes based on fully homomorphic encryption (FHE) [19] or multi-layer onion additively homomorphic encryption [20] are also

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1. N is the number of real data items in the storage system.

not suitable for MCS due to complex client-side encryption and decryption computation, although they circumvent the communication lower bound and achieve constant communication bandwidth overhead. Third, many existing oblivious schemes are also suffered by the lager minimum effective item size. Minimum effective item size refers to the minimal number of bits in an effective item of an oblivious scheme required to meet the predefined communication complexity (constant or logarithmic). Lager item size prevents the mobile client from fine-grained accessing its own data. Moreover, it also further increases the communication and computation overhead of existing oblivious schemes.

Some oblivious schemes consider to introduce data locality to improve efficiency. Data locality reveals the tendency of a client to access its data over a short time. Spatial locality and temporal locality are two typical types of reference locality of data access. Spatial locality refers that the client may access the nearby data items if a particular item is accessed. Temporal locality refers that the client will reuse data repeatedly within a short time. By taking spatial locality into consideration in non-constant communication overhead oblivious schemes, the amortized communication overhead whiling accessing a series of items can be lower than that whiling accessing one item independently [21]. Taking advantage of temporal locality can also significantly improve efficiency of particular oblivious schemes since if an item has been visited, it only requires lightweight computation and communication to access the item again in a short time. However, as far as we know, there is no related work that has considered temporal locality.

In this paper, we propose an efficient, secure and privacy-preserving mobile cloud storage scheme. The proposed scheme has the following properties: 1) protecting data confidentiality and access pattern simultaneously, 2) constant communication bandwidth overhead, 3) low client-side computation (a few additively homomorphic encryption and decryption operations), 4) small minimum effective item size (several kilobytes for reasonable data capacity), 5) taking temporal locality into consideration, and 6) verifiable (against malicious cloud). Specifically, we highlight our contributions of this paper in the following.

- We define a two-party protocol, i.e., oblivious selection and update (OSU) protocol, and present a concrete construction of OSU protocol. OSU allows a client to obliviously retrieve its encrypted data from the cloud and update the data with fresh values. Compared with other methods, such as PIR-Read combined PIR-Write, OSU requires less communication and client computation. For particular data size, the proposed OSU has $O(1)$ communication complexity and requires the client to execute minimum encryption and decryption operations. Moreover, the protocol is of independent interest for other secure multi-party computation application scenarios.
- Based on the proposed OSU protocol, we present an efficient, secure and privacy-preserving mobile cloud storage scheme. The scheme can simultaneously protect data content and preserve access pattern privacy. Compared with previous works, our scheme has small item size, low client-side computation, and constant communication overhead. We also introduce temporal locality into our construction to further enhance the efficiency. By combining "verification chunks" method, our scheme can be verifiable and resist malicious cloud. Furthermore, we evaluate our construction and other related works and the experimental performances show that our scheme is more efficient.

Organization. The remainder of the paper is organized as follows. In Section 2, we review some related works. In Section 3, we introduce the system model and threat model of the mobile cloud storage. The preliminaries as well as the oblivious selection and update protocol are described in Section 4. Our proposed mobile cloud storage scheme and the proofs and analyses are introduced in Sections 5 and 6, respectively. Finally, we give the evaluation and conclusion in Sections 7 and 8.

2 Related Works

Goldreich and Ostrovsky introduced the first concept, oblivious random access machine (ORAM), to preserve access pattern privacy [4]. They proposed a concrete solution, Square Root ORAM, and demonstrated a communication overhead lower-bound blowup $\Omega(\log N)$. In their setting (passive setting), the memory, or cloud in cloud computing application, acted as a passive storage entity and did not execute any computation on data. Under this setting, a series of works had been improved in terms of theory and efficiency [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. Shi *et al.* first organized their construction into a binary tree over buckets [24]. By operating blocks along tree paths, the proposed construction achieved $O(\log^3 N)$ communication worst-case cost. Path ORAM [26] was proposed by Stefanov *et al.* based upon the binary tree ORAM framework. It achieved the $\Omega(\log N)$ lower-bound blowup demonstrated by Goldreich and Ostrovsky [4] in passive setting. Path ORAM was also extremely simpler than other constructions by avoiding using complicated cryptographic primitives and efficient with small end-to-end delay for reasonable parameters.

Actually, the current cloud is considered to have significant computational resource and can execute heavy computation. A series of subsequent works followed the computation cloud setting and circumvented the lower-bound by allowing the cloud to execute heavy computation for the client [19], [20], [34]. Although it was not the first one to adopt cloud computation model, Apon *et al.* first formalized the verifiable oblivious storage, which generalizes the notion of ORAM by allowing the storage medium to perform computation [19]. Devadas *et al.* proposed a constant communication bandwidth ORAM, i.e., Onion ORAM, with cloud computation [20]. In Onion ORAM, data blocks were encrypted under multi-layer (forming as an "onion") additively homomorphic encryption scheme [35] or alternatively somewhat homomorphic encryption scheme [36], which allowed the client to retrieve the target blocks and evict blocks through paths with small encrypted select vectors. By combining the reverse lexicographical eviction order method [16], Onion ORAM overflowed with negligible probability for eligible security parameters. Moataz *et al.* proposed another constant communication bandwidth ORAM named C-ORAM [34]. Compared

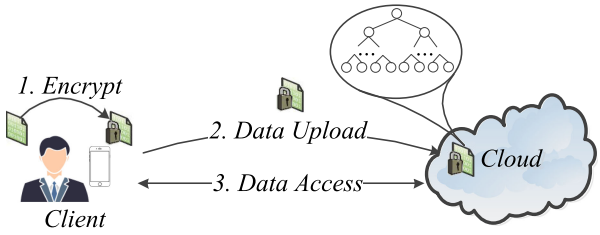


Fig. 1. System model.

with Onion ORAM, C-ORAM removed layered homomorphic encryption and replaced it with an efficient oblivious merging technique. This significantly reduced the required block size and the computation cost on the cloud side.

Recently, some related works considered data locality in OS/ORAM schemes [21], [37], [38], [39]. In [38], the authors identified a type of program locality in recursive ORAM scheme operations to improve performance. In [39], Asharov *et al*. formally studied locality-preserving ORAMs, which preserved locality of the accessed memory regions, while leaking only the lengths of contiguous memory regions accessed.

3 Background

3.1 System Model

As shown in Fig. 1, there are two entities involved in a mobile cloud storage system, e.g., *client* ($\mathcal{C}$) and *cloud* ($\mathcal{S}$). The client $\mathcal{C}$ first employs some technologies to protect its data, such as encryption schemes. Then it uploads its encrypted data into a remote cloud server $\mathcal{S}$. After that, the client $\mathcal{C}$ can access its data via a mobile device, such as mobile phone, tablet or laptop computer. The client's data is represented as a "key-value" form similar to most cloud storage services. Specifically, the cloud supports the following fundamental access operations.

- $\mathsf{get}(\mathsf{k})$. If there is an item labeled with the key k (abbr. item k) in the storage, then returns the corresponding value to the client, else returns $\perp$.
- $\mathsf{put}(k, v^*)$. If the item k is in the storage, then updates the value of this item with v^*, else inserts a new item tuple (k, v^*) to the storage.
- $\mathsf{remove}(k)$. If the item k is in the storage, then deletes the item from the storage.

Communication Model. In the system, the communication channel between the client and the cloud is considered to be secure. That means the *confidentiality* and *integrity* of all messages in the channel are guaranteed. This condition can be easily achieved with standard cryptographic tools, such as public key encryption, digital signature and public key infrastructure (PKI). This helps to simplify the description of our scheme.

3.2 Security Definition

Most of the existing constant communication bandwidth overhead works [20], [34] adopt the standard security definition for ORAMs from [25]. The standard security definition requires that the cloud server $\mathcal{S}$ cannot distinguish any two data access sequences of the same length, and provides a very strong security guarantee.

However, this security definition cannot be directly adopted in our work since considering temporal locality in storage system will inevitably reveal partial access pattern of the client's accesses. For instance, suppose there are two data access sequences $\overrightarrow{X}, \overrightarrow{Y}$ with length l. In the data access sequence $\overrightarrow{X}$, the client repeatedly accesses an item l times. In the data access sequence $\overrightarrow{Y}$, the client accesses l different items. When the client invokes the data access sequence $\overrightarrow{X}$ or $\overrightarrow{Y}$, the cloud can only observe that the client accesses l items if temporal locality is not considered. However, if temporal locality is taken into consideration, the cloud will distinguish the two data access sequences since the computation or communication overhead during invoking $\overrightarrow{X}$ is less than that during invoking $\overrightarrow{Y}$.[2]

Therefore, we adopt a restricted security definition, $\mathcal{R}$-indistinguishability, for the proposed secure and privacy-preserving mobile cloud storage to involve temporal locality. Informally, for any access request sequence, the $\mathcal{R}$-indistinguishability requires 1) the cloud can not learn which items the client has accessed, 2) the cloud can not gain any information of the values, and 3) the cloud may infer that the client has repeatedly accessed some items, but does not know the specific keys or the operation types.

Definition 1 ($\mathcal{R}$-indistinguishability). *Let* $\overrightarrow{Y} = (y_1, y_2, \ldots, y_m)$ *be an item access request sequence of length* $|\overrightarrow{Y}| = m$, *where* $y_i = (op_i, k_i, v_i^*)$ *is an item access request.* $\mathcal{A}(\overrightarrow{Y})$ *be the access pattern of* $\overrightarrow{Y}$ *observed by the cloud.* $\mathcal{R}(\overrightarrow{Y})$ *is a set describing the relationships of the keys of items, where* $\mathcal{R}(\overrightarrow{Y}) = \{(i,j)|(k_i = k_j) \wedge (i < j)\}$.

We say a protocol satisfies $\mathcal{R}$-indistinguishability, if for any item access request sequences $\overrightarrow{Y}$ *and* $\overrightarrow{Z}$ *with* $|\overrightarrow{Y}| = |\overrightarrow{Z}|$ *and* $\mathcal{R}(\overrightarrow{Y}) = \mathcal{R}(\overrightarrow{Z})$, *the access patterns* $\mathcal{A}(\overrightarrow{Y})$ *and* $\mathcal{A}(\overrightarrow{Z})$ *are computationally indistinguishable to the cloud, denoted by* $\mathcal{A}(\overrightarrow{Y}) \overset{c}{\approx} \mathcal{A}(\overrightarrow{Z})$.

In fact, the proposed $\mathcal{R}$-indistinguishability is the same as the standard security definition except that it has stronger restriction on the access request sequence. Thus, the $\mathcal{R}$-indistinguishability also implies data confidentiality and access pattern preservation. In this paper, we further consider that the cloud can be malicious. In this situation, the cloud can violate the protocol and try its best to gain more information from the client. As well as previous works, we also do not consider information leakage through the timing channel, such as when or how frequently the client makes data requests.

4 Preliminaries

In this section, we briefly introduce some preliminaries which are employed in our scheme. Then we present an oblivious selection and update (OSU) protocol, which is a building block of the proposed secure and privacy-preserving mobile cloud storage scheme.

4.1 Additively Homomorphic Encryption

Homomorphic encryption is a form of public key encryption. It allows anyone with the public key to manipulate ciphertexts to generate a new ciphertext, which is encrypted of corresponding operation result of original plaintexts.

2. Otherwise, it is meaningless to consider temporal locality.

Compared with fully homomorphic encryption, additively homomorphic encryption (AHE) scheme only supports homomorphic additive operation, but has higher efficiency. In our scheme, we employ a special AHE scheme, i.e., Damgård-Jurik construction [35]. In this AHE construction, ciphertexts are hierarchical, which means the lower layer ciphertext can be encrypted into a higher layer. Additionally, for two ciphertexts in the same layer, anyone with the public key can execute homomorphic additive operation on them without decrypting. Specifically, there are three algorithms in Damgård-Jurik construction.

- *Key Generation*. The algorithm takes input a security parameter κ and generates an RSA modulus $n = pq$, where $|p| = |q| = \kappa$. Then the public key is n while the secret key is the least common multiple $\lambda = Lcm(p-1, q-1)$.
- *Encryption*. To encrypt a message $m \in \mathbb{Z}_{n^s}$, the algorithm first chooses a random number $r \in \mathbb{Z}^*_{n^{s+1}}$, and sets the ciphertext as $c = (1+n)^m \cdot r^{n^s} \bmod n^{s+1}$.[3]
- *Decryption*. To decrypt a ciphertext $c \in \mathbb{Z}^*_{n^{s+1}}$, the algorithm first computes a number d, such that $d = 1 \bmod n^s$ and $d = 0 \bmod \lambda$ by the Chinese Remainder Theorem. Then computes

$$\begin{aligned} c^d &= ((1+n)^m \cdot r^{n^s})^d \\ &= (1+n)^{md \bmod n^s} \cdot (r^{n^s})^{d \bmod \lambda} \\ &= (1+n)^m \bmod n^{s+1}. \end{aligned}$$

  After that, invokes the algorithm described in [35] to retrieve $m \bmod n^s$ from $(1+n)^m \bmod n^{s+1}$.

Note that, when encrypting a message $m \in \mathbb{Z}_{n^s}$ into the s layer to get a ciphertext $c \in \mathbb{Z}_{n^{s+1}}$, the ciphertext is also in the $s+1$ layer plaintext space and can be encrypted again to get another ciphertext $c' \in \mathbb{Z}_{n^{s+2}}$. Accordingly, to retrieve the message m from the ciphertext c', the decryption algorithm should be executed twice with decrypting parameters $s+1$ and s, respectively. For convenience, we use the notation $[\![m]\!]_l$ to denote the AHE ciphertext directly encrypted $m \in \mathbb{Z}_{n^l}$ into the l layer. We also use $\circ$ to represent the homomorphic addition operation: $[\![m_1]\!]_l \circ [\![m_2]\!]_l = [\![m_1 + m_2]\!]_l$.

Moreover, we independently explore the following useful property of Damgård-Jurik construction. In this cryptosystem, if a ciphertext is encrypted of a message from a lower layer message space into a higher level, this ciphertext can be reduced to the lower layer without decrypting it. For example, a message $m \in \mathbb{Z}_{n^u}$ can be encrypted in wth layer to get the ciphertext $[\![m]\!]_w$, where $w > u$. Then we can easily transform the ciphertext $[\![m]\!]_w$ into the v layer to get a new ciphertext $[\![m]\!]_v$, where $w > v \geq u$, by computing $[\![m]\!]_v = [\![m]\!]_w \bmod n^{v+1}$. The detail of this property is shown in Appendix A, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TDSC.2020.3027579.

4.2 Oblivious Selection and Update Protocol

Here, we describe a notion named oblivious selection and update (OSU) protocol. In this two-party protocol, a client $\mathcal{C}$ securely stores a set of data in a cloud $\mathcal{S}$. Then, the client $\mathcal{C}$ can obliviously retrieve a target data item from the cloud and update it with another value by generating a small vector. We believe this protocol will be of independent interest in many secure multi-party computation scenarios. Formally, the oblivious selection and update protocol is defined as follows.

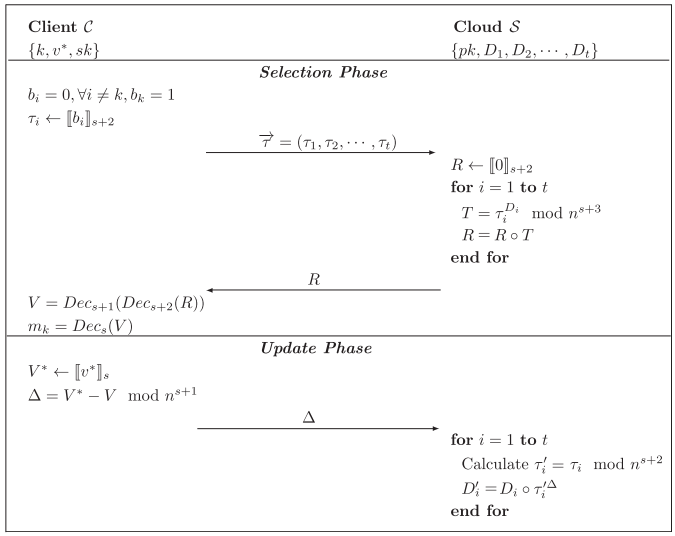


Fig. 2. The oblivious select and update protocol.

Definition 2 (Oblivious Selection and Update Protocol). *A two-phase oblivious selection and update protocol is an interactive protocol between a client and a cloud with two phases i.e., selection phase and update phase. In the protocol, the cloud takes input a set of protected data set $\mathcal{D} = \{D_1, D_2, \ldots, D_t\}$ and public information, e.g., public key pk, and the client takes input an index k ($1 \leq k \leq t$), a fresh value v^* and its secret information, e.g., secret key sk. At the end of the selection phase, the client will get D_k. At the end of the update phase, D_k will be updated by the fresh value v^* and D_i will remain unchanged for all $i \neq k$. During the protocol, the cloud learns nothing about the data set $\mathcal{D}$ or the index k. Formally, the following notations are used to denote the two phases of OSU.*

$$(D_k;\ \perp) \leftarrow OSU^1(k, sk;\ \mathcal{D}, pk),$$
$$(\perp;\ \mathcal{D}') \leftarrow OSU^2(D_k, k, v^*, sk;\ \mathcal{D}, pk).$$

It easy to know that data D_i should be protected by probabilistic method, such as probabilistic encryption. Otherwise, the cloud will learn the index k while updating D_k with the fresh value v^*. Besides, the fresh value v^* is not necessary until the update phase. Thus, the client can determine the fresh value v^* after obtaining D_k.

We describe our oblivious selection and update protocol construction in Fig. 2. Suppose that the client owns a key pair of an AHE scheme. Then it encrypts its data $m_1, m_2, \ldots, m_t \in \mathbb{Z}_{n^s}$ with its public key and stores them in the cloud as $D_i \leftarrow [\![[\![m_i]\!]_s]\!]_{s+1}$. After that, the client can invoke OSU to retrieve and update the target data item.

In order to retrieve the kth data item, the client first generates a vector $\overrightarrow{b} = (b_1, b_2, \ldots, b_t)$, where each $b_i = 0$ except

3. Here s is a positive integer with $s < p, q$.

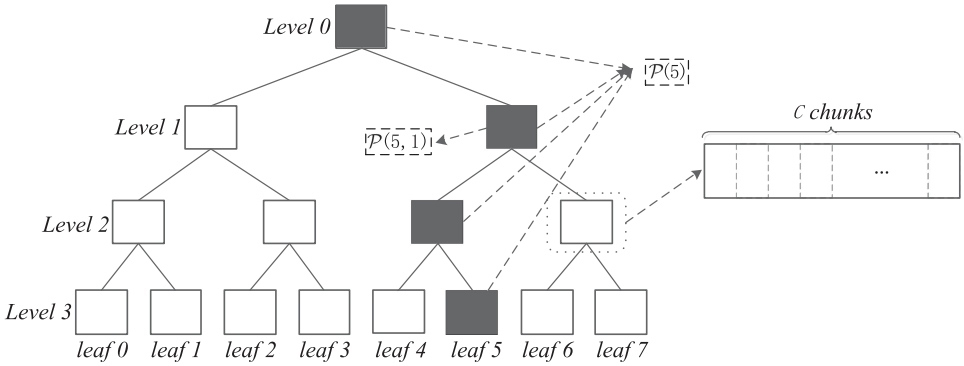


Fig. 3. Data structure on cloud side.

$b_k = 1$. Then, the client encrypts each b_i with AHE public key into $s+2$ layer and sends all $\tau_i \leftarrow [\![b_i]\!]_{s+2}$ to the cloud. With the encrypted vector $\overrightarrow{\tau}$, the cloud first sets a new ciphertext, R, as encrypting of 0 into $s+2$ layer. Then for each D_i, the cloud computes $T_i = \tau_i^{D_i} \bmod n^{s+3}$ and $R = R \circ T_i$. After that, the cloud returns R to the client. At the end of this phase, the client decrypts R twice to get V and decrypts V once to get m_k.

In the update phase, the client first encrypts the fresh value v^* into s layer to get ciphertext V^* and computes $\Delta = V^* - V \bmod n^{s+1}$. Then it sends Δ to the cloud. The cloud uses the above AHE property to re-compute τ_i', which is a new ciphertext of encrypting of b_i into $s+1$ layer. Then the cloud updates all encrypted data D_i as D_i' by multiplying $\tau_i'^{\Delta}$. Finally, the D_k' will be updated by the new value v^* and other data items have no changes.

Correctness. Note that, each data item D_i is encrypted of m_i twice into s and $s+1$ layers, and τ_i is encrypted of b_i into $s+2$ layer. Therefore, D_i is in the plaintext space of τ_i. Thus, according to the homomorphic addition property of AHE scheme, we have

$$\begin{aligned}\tau_i^{D_i} \bmod n^{s+3} &= [\![b_i \cdot D_i]\!]_{s+2} \\ &= \begin{cases} [\![0]\!]_{s+2}, & i \neq k \\ [\![D_i]\!]_{s+2}, & i = k. \end{cases}\end{aligned} \tag{1}$$

Then, $R = [\![D_k]\!]_{s+2} = [\![[\![[\![m_k]\!]_s]\!]_{s+1}]\!]_{s+2}$. Therefore, the client can decrypt R three times to get m_k.

In the update phase, the cloud can calculate $\tau_i' \leftarrow \tau_i \bmod n^{s+2}$ as encrypting of b_i into $s+1$ layer according to the mentioned property of the AHE scheme. Since $V^* \leftarrow [\![v^*]\!]_s$ and $V = [\![m_k]\!]_s$ are all in s layer ciphertext space, the difference Δ of V^* and V is also in s layer ciphertext space as well as in $s+1$ layer plaintext space. Therefore, $\tau_i'^{\Delta}$ is encrypted of $b_i \cdot \Delta$ into $s+1$ layer. Let $U_i = \tau_i'^{\Delta}$, then we have

$$\begin{aligned}U_i = \tau_i'^{\Delta} \bmod n^{s+2} &= [\![b_i \cdot \Delta]\!]_{s+1} \\ &= \begin{cases} [\![0]\!]_{s+1}, & i \neq k \\ [\![\Delta]\!]_{s+1} = [\![V^* - V]\!]_{s+1}, & i = k. \end{cases}\end{aligned} \tag{2}$$

Thus,

$$\begin{aligned}D_i' = D_i \circ U_i &= [\![[\![m_i]\!]_s]\!]_{s+1} \circ U_i \\ &= \begin{cases} [\![[\![m_i]\!]_s + 0]\!]_{s+1} \\ \quad = [\![[\![m_i]\!]_s]\!]_{s+1}, & i \neq k \\ [\![[\![m_k]\!]_s + V^* - V]\!]_{s+1} \\ \quad = [\![V^*]\!]_{s+1} = [\![[\![v^*]\!]_s]\!]_{s+1}, & i = k. \end{cases}\end{aligned} \tag{3}$$

Finally, the cloud obliviously updates the kth data item with v^* and leaves other items with no changes. □

We describe the above OSU in semi-honest setting. In the construction of our mobile cloud storage system, we will improve it into malicious setting.

5 The Proposed Construction

In this section, we present our efficient, secure, and privacy-preserving mobile cloud storage scheme, which is suitable for lightweight application and against malicious cloud server. We first describe the data structure and notations which are used in our construction. Then we introduce the initialization and access protocols.

5.1 Data Structure and Notations

We adopt binary tree based model in our construction. As shown in Fig 3, the data in the cloud is organized as a binary tree $\mathcal{T}$. Suppose there are N real items in the mobile cloud storage system. The height of the tree is L, where $2^{L+1} > N \geq 2^L$. Thus, there are 2^L leaves in $\mathcal{T}$ which are labeled with number $0, 1, \ldots, 2^L - 1$ from left to right at the last level of $\mathcal{T}$. In our construction, each node/bucket of $\mathcal{T}$ only contains one single real item. Thus, we will indiscriminately use the word "bucket" to indicate data item. Each bucket contains C chunks and encodes the item (k, v), i.e., the key and the value of the item. For a leaf l, the operation $\mathcal{P}(l)$ returns all $L+1$ buckets on the path from the root to the leaf and $\mathcal{P}(l, p)$ returns the pth bucket of $\mathcal{P}(l)$, where $0 \leq p \leq L$.

The client maintains a stash σ and a position map **pm**. The position map **pm** is a dictionary and maps the mobile cloud storage system from logical key of item to physical storage location. For a key k of an item, the position map $\mathbf{pm}[k]$ returns a location tuple (l, p) indicated that the item may be located at the $\mathcal{P}(l, p)$ node of $\mathcal{T}$, alternatively a

TABLE 1
Notations

$\mathcal{T}$	The tree structure.
L	The depth of $\mathcal{T}$.
N	The number of real items.
C	The number of chunks in each bucket.
B	Item size.
B_C	Chunk size ($B = B_C \cdot C$).
$\mathcal{P}(l)$	The path from the root to the lth leaf.
$\mathcal{P}(l,p)$	The pth bucket of $\mathcal{P}(l)$, $0 \le p \le L$.
σ	The stash.
t, Z	The parameters of the stash σ.
pm	The position map.
$x \xleftarrow{\$} \mathcal{S}$	Randomly and uniformly select x from $\mathcal{S}$.

symbol $\perp$ indicated that the item does not exist in the storage system. The stash σ is a two-dimensional array. It contains $t \cdot Z$ slots and temporarily stores items which are not updated into the $\mathcal{T}$. Each slot in σ is a tuple in the form of (k, v). The stash σ consists the following four operations.

- $\sigma.push(k, v)$. This operation stores the item (k, v) into σ.
- $\sigma.update(k, I')$. This operation updates a slot of σ indicated by k with a tuple I'.
- $v \leftarrow \sigma.get(k)$. This operation returns a value v of an item from σ which is indicated by k.
- $(k, v) \leftarrow \sigma.pop()$. This operation *removes* and *returns* an item tuple (k, v) from σ.

The main notations are shown in Table 1.

5.2 Initialization Phase

Suppose the client has an item tuple set $\mathcal{I} = \{(k_i, v_i)\}, |\mathcal{I}| \le N$. Then, the client invokes the **Init**$(\mathcal{I})$ algorithm to initialize the mobile cloud storage system, i.e., the stash σ, the position map **pm** and the data structure $\mathcal{T}$, as shown in Fig. 4. The client first generates a Damgård-Jurik cryptosystem [35] key-pair and initializes the stash σ, the position map **pm** and the tree $\mathcal{T}$, respectively. Then, for each item tuple in the set $\mathcal{I}$, the client randomly stores it into an empty bucket (l_i, p_i) of $\mathcal{T}$ and correspondingly updates the position map, where $l_i \in [0, 2^L)$ and $p_i \in [0, L]$. Since $|\mathcal{I}| \le N$, there is always enough empty buckets to store the item tuple set. After storing all items into $\mathcal{T}$, the client sets all remaining empty buckets to be random values. For each bucket, the client divides it into C chunks and encrypts each chunk twice with Damgård-Jurik cryptosystem public key. Finally, the client sends the encrypted data structure $\mathcal{T}$ to the Cloud.

5.3 Access Phase

In order to protect the type of operation from the cloud, we design a single uniform interface, i.e., access protocol, to perform all the previously defined operations. As shown in Fig. 5, the access protocol **Access**(op, k, v^*) takes input as a triple (op, k, v^*). Here, operation op can be get, put or remove and the key k indicates the item where the client wants to operate. The value v^* is a fresh value if $op =$ put and a placeholder value if $op =$ get or $op =$ remove. Additionally, we set that the **Access** protocol always returns the original value of the item indicated by the key k even the operation is put or remove. This setting helps reduce the computation overhead of the client when performing certain special operations. For instance, if the client wants to read an item indicated by key k and then update it with a fresh value v^*, the client can directly invoke the protocol $v \leftarrow$ **Access**(put, k, v*). Specially, the process of **Access** has the following steps.

Init$(\mathcal{I})$

1: Generate a key-pair of Damgård-Jurik cryptosystem, i.e. public key pk and secret key sk.
2: Choose a suitable encryption parameter s.
3: Set the **pm** and all bucket of $\mathcal{T}$ to be empty.
4: Initialize $\sigma[i][j]$ to be dummy item tuple for all $1 \le i \le t, 1 \le j \le Z$.
5: **for** $i = 1$ to $|\mathcal{I}|$ **do**
6: Randomly choose an empty bucket (l_i, p_i) in $\mathcal{T}$.
7: Set $\mathcal{P}(l_i, p_i)$ as (k_i, v_i).
8: Set $\mathbf{pm}[k] = (l_i, p_i)$.
9: **end for**
10: **for** each bucket $\mathcal{B}$ in $\mathcal{T}$ **do**
11: **if** $\mathcal{B}$ is empty **then**
12: Set $\mathcal{B}$ as dummy tuple.
13: **end if**
14: $\mathcal{C} \leftarrow Encode(\mathcal{B})$, where $\mathcal{C} = \{\mathcal{C}_j : \mathcal{C}_j \in \mathbb{Z}_{n^s} \wedge 1 \le j \le C\}$.
15: **for** $j = 1$ to C **do**
16: $\widehat{\mathcal{C}_j} \leftarrow [\![[\![\mathcal{C}_j]\!]_s]\!]_{s+1}$.
17: **end for**
18: Replace the bucket with $\widehat{\mathcal{C}} = \{\widehat{\mathcal{C}_j} : 1 \le j \le C\}$.
19: **end for**
20: Send the encrypted tree $\mathcal{T}$ and the public key pk to the cloud.

Fig. 4. The initialization algorithm.

1. **Item remap** (Lines 1 to 10): The client gets the location of the bucket where the item is located in $\mathcal{T}$ and reassigns a new random location to the item.
2. **Item select** (Line 11-17): The client obliviously gets the target bucket from $\mathcal{T}$, retrieves an item tuple from the bucket and stores the item tuple into the stash if the item is valid.
3. **Result record** (Lines 18 to 29): The client recodes the result and updates the item if needed.
4. **Item rewrite and pm update** (Lines 30 to 35): The client pops out an item tuple (k_b, v_b), obliviously writes it back to the location $\mathcal{P}(l_a, p_a)$, and updates the position map $\mathbf{pm}[k_b]$.
5. **Result return** (Line 36): The client returns the item indicated by the key k.

In our construction, when the client wants to access (get, put or remove) an item k, it first checks the existence of the item. If the item does not exist, the protocol aborts except that the operation $op =$ put. In this situation, the client sets the flag as 1 and (l_a, p_a) as a random location stored a dummy tuple in $\mathcal{T}$. It is worth noting that if the item k is in the stash before accessing, $\mathcal{P}(l_a, p_a)$ will be an irrelevant item or a dummy item. If the protocol does not abort, the client randomly chooses another location (l', p') and updates $\mathbf{pm}[k]$ with the new location.

Access(op, k, v^*)

1: $flag = 0$
2: **if** $\mathbf{pm}[k]$ exists **then**
3: $(l_a, p_a) \leftarrow \mathbf{pm}[k]$
4: **else if** $op ==$ put **then**
5: $flag = 1$
6: Randomize $l_a \xleftarrow{\$} [0, 2^L)$, $p_a \xleftarrow{\$} [0, L]$, where $\mathcal{P}(l_a, p_a)$ stores a dummy tuple.
7: **else**
8: **return** $\perp$
9: **end if**
10: $\mathbf{pm}[k] \leftarrow (l', p')$, where $l' \xleftarrow{\$} [0, 2^L)$, $p' \xleftarrow{\$} [0, L]$

11: The client invokes the selection phases of OSU: $(\mathcal{P}(l_a, p_a); \perp) \leftarrow OSU^1(p_a, sk; \mathcal{P}(l_a), pk)$.
12: Retrieve the item (k_a, v_a) by decrypting and decoding $\mathcal{P}(l_a, p_a)$.
13: **if** $flag == 1$ **then**
14: $\sigma.push(k, \text{null})$.
15: **else**
16: $\sigma.push(k_a, v_a)$.
17: **end if**

18: $v \leftarrow \sigma.get(k)$
19: **if** $op ==$ get **then**
20: $I' \leftarrow (k, v)$
21: **else if** $op ==$ put **then**
22: $I' \leftarrow (k, v^*)$
23: **else if** $op ==$ remove **then**
24: $I' \leftarrow d$, where d is a dummy item tuple.
25: Remove $\mathbf{pm}[k]$ from the position map.
26: **else**
27: **return** $\perp$
28: **end if**
29: $\sigma.update(k, I')$

30: $(k_b, v_b) \leftarrow \sigma.pop()$, let $\tau_b = (k_b, v_b)$.
31: The client continues to invoke the update phase of OSU: $(\perp; \mathcal{P}(l_a)') \leftarrow OSU^2(\mathcal{P}(l_a, p_a), p_a, \tau_b, sk; \mathcal{P}(l_a), pk)$.
32: **if** τ_b is not a dummy tuple **then**
33: $l'_a \xleftarrow{\$} S$, where $S = \{l : \mathcal{P}(l, p_a) = \mathcal{P}(l_a, p_a)\}$.
34: $\mathbf{pm}[k_b] \leftarrow (l'_a, p_a)$
35: **end if**

36: **return** v

Fig. 5. The access protocol.

With the location (l_a, p_a), the client invokes the selection phase of OSU to obliviously select the target bucket $\mathcal{P}(l_a, p_a)$ from the cloud. Then it decrypts and decodes the encrypted bucket to retrieve an item tuple (k_a, p_a). Since there are dummy tuples in the $\mathcal{T}$, the client checks the tuple (k_a, p_a). If the *flag* equals 1, (k_a, p_a) must be a dummy tuple. In this situation, the client invokes $\sigma.push(k, \text{null})$, where null is an empty value. Otherwise, the client store (k_a, p_a) into the stash by invoking $\sigma.push(k_a, p_a)$. As we mentioned before, the item key k_a may not equal k. However, after pushing operation, the item indicated by k is in the stash σ with overwhelming probability. The correctness of our protocol will be discussed later.

Since the item k is already in the stash, the client can easily get the corresponding value v from the stash. Then, if the access is a put operation, the client updates the item with the new fresh value v^*. Accordingly, if the access is a remove operation, the client updates the item with a dummy tuple and removes $\mathbf{pm}[k]$ from the position map.

After recording the access request result, the client invokes $\sigma.pop()$ to select another tuple (k_b, v_b)[4] from the stash and updates the node $\mathcal{P}(l_a, p_a)$ with the tuple by sequentially invoking the update phase of OSU. To ensure consistency, if (k_b, v_b) is a valid item, the position map of (k_b, v_b) is also reassigned to the position tuple (l'_a, p_a) where $\mathcal{P}(l'_a, p_a) = \mathcal{P}(l_a, p_a)$.

In our construction, the stash σ is organized as a two-dimensional array with t rows and Z columns, where $t, Z \geq 2$. Each slot in the stash $\sigma[i][j]_{1 \leq i \leq t, 1 \leq j \leq Z}$ is initialized as a dummy item tuple. The operations of the stash are described in Fig. 6.

5.4 Correctness of Access Protocol

We propose the following Theorem 1 to describe the correctness of the **Access** protocol.

Theorem 1. *For any valid access request, the* **Access** *protocol always returns correct result with overwhelming probability.*

Proof. We assume that the mobile cloud storage system is initialized correctly, i.e., all data items are encrypted correctly and stored in $\mathcal{T}$, all slots of the stash are initialized as dummy tuples, and the position map records correct positions for all data items. We also assume that the system does not overflow after a put operation.

Note that, since the client always invokes the pop operation of the stash after the push operation during an access request, there is always at least one dummy (empty) tuple in the first row of σ for pushing the retrieved item tuple during the next access request. For each access request (op, k, v^*), if the item indicated by k exists in the storage system, it is either in the $\mathcal{T}$ or in the stash σ at the beginning of the access request.

- The item k is in the $\mathcal{T}$. In this situation, the item k should be never retrieved into the stash or it had been updated into the $\mathcal{T}$ during a previous access request (op', k', v'). If the item is never retrieved into the stash, since the storage system is initialized correctly, the client always retrieves the item from $\mathcal{T}$ and stores it into the stash by invoking the selection phase of OSU. Otherwise, the item had been updated into the $\mathcal{T}$ during the a previous access request (op', k', v'). [5]According to the processes of the proposed **Access** protocol, the position map of the item k was also correspondingly updated while storing the item tuple indicated by k in $\mathcal{T}$ during the previous access request (op', k', v'). Thus, the position map always returns

4. (k_b, v_b) cloud be a dummy tuple.
5. Note that, k may be not equal k'.

$\sigma.push(k, v)$

1: $ptr \leftarrow 0$
2: **for** $j = 1; j++; j \leq Z$ **do**
3: **if** $\sigma[1][j]$ is a dummy tuple **then**
4: $ptr \leftarrow j$
5: **end if**
6: **end for**
7: **if** $ptr == 0$ **then**
8: **return** $\perp$
9: **end if**
10: $\sigma[1][ptr] \leftarrow (k, v)$
11: **return** 0

$\sigma.update(k, I')$

1: **for** $i = 1; i++; i \leq t$ **do**
2: **for** $j = 1; j++; j \leq Z$ **do**
3: **if** $\sigma[i][j].k == k$ **then**
4: $\sigma[i][j] \leftarrow I'$
5: **return** 0
6: **end if**
7: **end for**
8: **end for**
9: **return** $\perp$

$v \leftarrow \sigma.get(k)$

1: **for** $i = 1; i++; i \leq t$ **do**
2: **for** $j = 1; j++; j \leq Z$ **do**
3: **if** $\sigma[i][j].k == k$ **then**
4: **return** $\sigma[i][j].v$
5: **end if**
6: **end for**
7: **end for**
8: **return** 0

$(k, v) \leftarrow \sigma.pop()$

1: **for** $i = t; i--; i \geq 1$ **do**
2: $ptr[i] \xleftarrow{\$} [1, Z]$
3: **if** $i == t$ **then**
4: $(k, v) \leftarrow \sigma[i][ptr[i]]$
5: **else**
6: $\sigma[i+1][ptr[i+1]] \leftarrow \sigma[i][ptr[i]]$
7: **end if**
8: **if** $i == 1$ **then**
9: Set $\sigma[i][ptr[i]]$ as dummy tuple.
10: **end if**
11: **end for**
12: **return** (k, v)

Fig. 6. The operations of σ.

correct location of the accessed item k while it is in the $\mathcal{T}$. The client can retrieve the corresponding bucket from $\mathcal{T}$, decrypt and decode the bucket to get the item tuple indicated by k, store the tuple into the stash, and update the tuple if $op =$ put or $op =$ remove.

- The item k is in the stash σ. In this situation, the item k has been retrieved from $\mathcal{T}$ during a previous access request (op', k', v') and not yet been updated in $\mathcal{T}$. Since the item k is still in the stash, the client can easily obtain and update it.

On the other hand, if the item indicated by k does not exist in the storage system, this access request must be a put operation. According to the processes of **Access** protocol, the item k will be inserted into the stash and a null value will be returned indicating that the item is newly inserted into the system.

That proves the **Access** protocol allows the client to obtain correct result from the mobile cloud storage system with overwhelming probability. □

5.5 Locality of Reference

Temporal locality refers that the client will reuse data repeatedly within a short time. To take advantage of temporal locality, we describe the $\mathbf{AccTemLoc}(op, k, v^*)$ protocol in Fig. 7.

In $\mathbf{AccTemLoc}(op, k, v^*)$ protocol, the client first checks whether the item k is in the stash. If the item is not in the stash, the client invokes $\mathbf{Access}'(op, k, v^*)$ protocol to access the item. The $\mathbf{Access}'(op, k, v^*)$ protocol is same as $\mathbf{Access}(op, k, v^*)$ except $\sigma.update(k, I')$ algorithm is replaced with $\sigma.update'(k, I')$ algorithm, which is described in Fig. 8. In the original $\sigma.update(k, I')$ algorithm, the client simply updates the item indicated by k with the item I', which is generated according to the access operation type and the value v^*. However, in $\sigma.update'(k, I')$ algorithm, the client first recodes the location of the item k in the stash. Then, it randomly rotates the item to the first row of the stash and updates it with the item I'. After that, the item k will be retained in the stash for at last t access request according to the pop policy of the stash. On the other hand, if the item k is already in the stash, the client does not require to interact with the cloud. This can significantly improve the efficient of mobile cloud storage system in many specific scenarios.

5.6 Resistance to Malicious Cloud

In the previous setting, we assume the cloud is semi-honest. That means the cloud will follow the protocol and correctly

$\mathbf{AccTemLoc}(op, k, v^*)$

1. On input an item access triple (op, k, v^*), the client first checks whether the item k exists in the stash σ. If not, the client invokes the $\mathbf{Access}'(op, k, v^*)$ protocol, which is same as $\mathbf{Access}(op, k, v^*)$ protocol except that the $\sigma.update(k, I')$ algorithm (line 29) is replaced by the $\sigma.update'(k, I')$ algorithm described in Fig. 8.
2. If the item k exists in the stash, the client simply invokes the **result record** (lines 18 to 29) step of $\mathbf{Access}'(op, k, v^*)$ protocol locally (non-interactively) to execute the access.

Fig. 7. The **AccTemLoc** protocol.

$\sigma.update'(k, I')$

1: **for** $i = 1; i++; i \leq t$ **do**
2: **for** $j = 1; j++; j \leq Z$ **do**
3: **if** $\sigma[i][j].k == k$ **then**
4: $\nu = i, f[\nu] = j$
5: **end if**
6: **end for**
7: **end for**
8: **for** $i = \nu - 1; i--; i \geq 1$ **do**
9: $f[i] \xleftarrow{\$} [1, Z]$
10: $\sigma[i+1][f[i+1]] \leftarrow \sigma[i][f[i]]$
11: **end for**
12: $\sigma[1][f[1]] \leftarrow I'$
13: **return** 0

Fig. 8. $\sigma.update'(k, I')$ algorithm.

respond all client's requests. However, due to many reasons, such as saving computation resources or learning information of access requests, the cloud may do not follow the protocol and be malicious. To against malicious cloud, Merkle tree-based integrity technology is used in several related works [26], [40]. However, in these constructions, the client retrieves a whole path of $\mathcal{T}$ from the cloud for each access request. Thus, this method is not suitable for our construction since the client only retrieves one node of access path in our construction. To ensure the client always retrieves correct node without revealing access request information to the malicious cloud, we can apply the "verification chunks" method [20] in our scheme.

The main idea of "verification chunks" method is allowing the client to select a random subset of chunks (ciphertext form) from the encrypted buckets and keep the subset of chunks as secret. Whenever the client invokes OSU on a path of $\mathcal{T}$, it first gets all verification chunks on this path from the cloud. Then the client can execute the same operation (selection and update) on the verification chunks. After retrieving an encrypted bucket from the cloud, the client can check whether the cloud returns correct bucket by comparing the operation results of verification chunks with the corresponding positions of the retrieved bucket. Correspondingly, in order to maintain consistency, the client also updates the verification chunks of each node on the path at the end of the access request. Moreover, the client can encode original data with an error-correcting code, such as Reed-Solomon code, to make the verification sufficiently. We show a complete workflow of "verification chunks" method in Appendix B, available in the online supplemental material.

6 Proofs and Analyses

In this section, we give the proofs and analyses of the proposed mobile cloud storage scheme in terms of the security, parametrization and complexity.

6.1 Security Proof

To prove the security of our construction (**AccTemLoc** protocol in semi-honest setting), we design a series of security games between the client and the cloud. The first security game is equivalent to the description in Definition 1 and the last security game is a totally input-independent game which perfectly hides the inputs of the client. Then we prove that the adjacent two games are computationally indistinguishable to the cloud. Specifically, the games are defined as follows.

Definition 3 (Game 0). *In the Game 0, the cloud chooses two item access request sequences $\overrightarrow{Y_0}$ and $\overrightarrow{Y_1}$ with the same length and $\mathcal{R}(\overrightarrow{Y_0}) = \mathcal{R}(\overrightarrow{Y_1})$. Then it sends $\overrightarrow{Y_0}$ and $\overrightarrow{Y_1}$ to the client. The client randomly flips a bit $\beta \in \{0, 1\}$ and invokes the item accesses in $\overrightarrow{Y_\beta}$ in order. The cloud observes the access pattern $\mathcal{A}(\overrightarrow{Y_\beta})$ and outputs a bit β'.*

Definition 4 (Game 1). *The Game 1 is the same as the Game 0 except that the client invokes item accesses in $\overrightarrow{Y^*}$ instead of $\overrightarrow{Y_\beta}$. Here, $\overrightarrow{Y^*}$ satisfies $\mathcal{R}(\overrightarrow{Y_\beta}) = \mathcal{R}(\overrightarrow{Y^*})$. Specially, $\overrightarrow{Y^*}$ is a copy of $\overrightarrow{Y_\beta}$, but replaces the item access triples that their indexes are not in $\mathcal{R}(\overrightarrow{Y_\beta})$ with random item access triples.*

We give an instance of $\overrightarrow{Y^*}$ in the Game 1. For example, if $\mathcal{R}(\overrightarrow{Y_\beta}) = \{(3, 6), (11, 12)\}$, $\overrightarrow{Y^*}$ should be a random item access request sequence except $y^*_3 = y_{\beta,3}$, $y^*_6 = y_{\beta,6}$, $y^*_{11} = y_{\beta,11}$, and $y^*_{12} = y_{\beta,12}$. Note that, If $\mathcal{R}(\overrightarrow{Y_\beta}) = \emptyset$, $\overrightarrow{Y^*}$ should be a totally random item access request sequence with $\mathcal{R}(\overrightarrow{Y^*}) = \emptyset$.

Definition 5 (Game 2). *The Game 2 is the same as the Game 1 except that the client invokes item accesses in $\overrightarrow{Y'}$, which is a random item access request sequence satisfied the constraints $|\overrightarrow{Y^*}| = |\overrightarrow{Y'}|$ and $\mathcal{R}(\overrightarrow{Y^*}) = \mathcal{R}(\overrightarrow{Y'})$.*

Lemma 1. *The Game 0 and Game 1 are computationally indistinguishable to the cloud.*

Proof. Compared with the Game 0, the client replaces the invoked item access triples in $\overrightarrow{Y_\beta}$ which are not in $\mathcal{R}(\overrightarrow{Y_\beta})$ with random triples in $\overrightarrow{Y^*}$ of the Game 1. According to the definition of $\mathcal{R}(\cdot)$, it is easy to know that these item access triples occurs only once in $\overrightarrow{Y_\beta}$. Since each item is randomly initialized in the $\mathcal{T}$, replacing these item accesses will not reveal any additional information to the cloud due to our access policy. Thus, we have $\mathcal{A}(\overrightarrow{Y_\beta}) \approx \mathcal{A}(\overrightarrow{Y^*})$. □

Lemma 2. *The Game 1 and Game 2 are computationally indistinguishable to the cloud.*

Proof. In the Game 2, the client invokes $\overrightarrow{Y'}$, which is further replaced the remained item access triples in $\overrightarrow{Y^*}$ with random triples, but retaining the restriction $\mathcal{R}(\overrightarrow{Y^*}) = \mathcal{R}(\overrightarrow{Y'})$. Now we analyze the access patterns of $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$ observed by the cloud. Let $\mathcal{R}$ denote $\mathcal{R}(\overrightarrow{Y'})$. For each tuple (i, j) in $\mathcal{R}$, we have $k^*_i = k^*_j$ and $k'_i = k'_j$ which are ith and jth accessed item keys in $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$, respectively. Suppose that the items k^*_i and k'_i have not been accessed before the ith access in $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$. Then, they has same probability to be retrieved from the cloud, stored in the stash and even written back to the $\mathcal{T}$ again in the previous item accesses. Thus, for the ith accesses in $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$, the probabilities of performing non-interactive access (situation 2 of **AccTemLoc** protocol) are the same. Since there

are the same number of item accesses between y_i^* to y_j^* and y_i' to y_j', it is also easy to know that the probabilities of performing non-interactive access are the same for the jth accesses of $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$. Finally, we have that the access patterns of $\overrightarrow{Y^*}$ and $\overrightarrow{Y'}$ have the same distribution, i.e., $\mathcal{A}(\overrightarrow{Y^*}) \approx \mathcal{A}(\overrightarrow{Y'})$. □

Theorem 2. *The proposed* **AccTemLoc** *protocol achieves $\mathcal{R}$-indistinguishability.*

Proof. In Game 2, the invoked item access request sequence $\overrightarrow{Y'}$ does not reveal any information of β since $\overrightarrow{Y'}$ is random except that it retains the same constraints as $\overrightarrow{Y_0}$ and $\overrightarrow{Y_1}$. Then the following equation holds

$$|\Pr^{Game_2}[\beta' = \beta] - \frac{1}{2}| = 0. \tag{4}$$

Combining the Lemma 1 and 2, the Game 0 and Game 2 are computationally indistinguishable to the cloud. Then

$$|\Pr^{Game_0}[\beta' = \beta] - \frac{1}{2}| = \epsilon, \tag{5}$$

where ϵ is a negligible value. That means the cloud has negligible probability to identity $\overrightarrow{Y_\beta}$ in the Game 0. Thus, we have that

$$\mathcal{A}(\overrightarrow{Y_0}) \overset{c}{\approx} \mathcal{A}(\overrightarrow{Y_1}). \tag{6}$$

That proves the Theorem 2. □

6.2 Parametrization of Probability

Now we discuss the probability of an item in the stash on the client side. Essentially, in our mobile cloud storage system, the stash plays the role of a mixed zone, to break the sequential relationship of items read from and written to the $\mathcal{T}$. Suppose an item k was first visited during the ith access. Then, at the end of the access, the item k was assigned to a random path and stored in the stash temporarily (at the first level of stash). According to the pop policy of the stash, the item k will remain in the stash during the next $t-1$ access requests. Accordingly, in the $(i+t)$-th and subsequent accesses, the item k will have a certain probability of being written back to the cloud.

Let E_s be the event of that the item k is written back to the $\mathcal{T}$ in the sth access,[6] where $s > i$. According to the pop policy of the stash, we have

$$\Pr[E_s] = \begin{cases} 0, & \Delta < t, \\ \binom{\Delta-1}{t-1}\rho^t(1-\rho)^{\Delta-t}, & \Delta \geq t, \end{cases} \tag{7}$$

where $\Delta = s - i$ and $\rho = \frac{1}{Z}$. Let the jth access be the nearest access for visiting the k item from the ith access, where $j > i$. The probability of the item k still in the stash at the beginning of jth access, as well as the probability of non-interactive access (situation 2 of **AccTemLoc** protocol) occurred, is

6. Suppose the item has not been visited in the $(i+1)$-th, $(i+2)$-th, ..., sth accesses.

TABLE 2
Item (block) Size of Constant Communication Bandwidth Overhead Schemes ($\lambda = \omega(\log N)$)

	Minimum effective item (block) size	Bandwidth Blowup
Onion ORAM	$\Omega(\gamma \log^2 \lambda \log^2 N)$	$O(1)$
C-ORAM	$\Omega(\lambda[\log \lambda \log N + \gamma])$	$O(1)$
Ours	$\Omega(\gamma \log N)$	$O(1)$

$$\Pr[In_k(i,j)] = 1 - \sum_{s=i+1}^{j-1} \Pr[E_s]. \tag{8}$$

Now we discuss the maximum of $\Pr[E_s]$, which indicates that in which access the item k is written back to the $\mathcal{T}$ with the highest probability. Still let E_s be the event defined above. By solving the following inequalities

$$\begin{cases} \Pr[E_{s-1}] \leq \Pr[E_s], \\ \Pr[E_s] \geq \Pr[E_{s+1}], \\ \Delta > t, \end{cases} \text{ or } \begin{cases} \Pr[E_s] \geq \Pr[E_{s+1}], \\ \Delta = t, \end{cases} \tag{9}$$

we can obtain the maximum of $\Pr[E_s]$ occurs when

$$\Delta = (t-1) \cdot Z, \tag{10}$$

or

$$\Delta = (t-1) \cdot Z + 1. \tag{11}$$

Then we have:

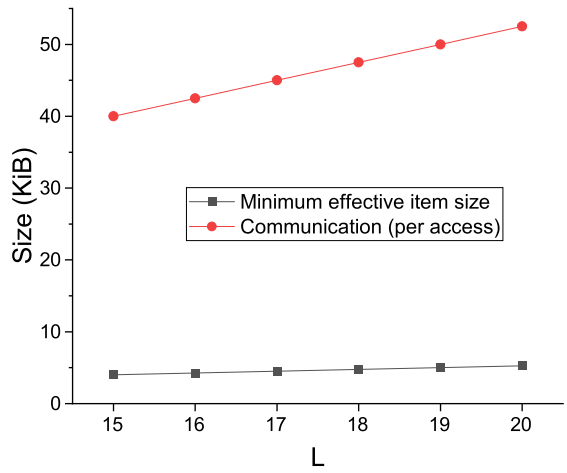
$$\begin{aligned} &\max\{\Pr[E_s]\} \\ &\quad = \max\{\Pr[E_{(t-1)\cdot Z+i}], \Pr[E_{(t-1)\cdot Z+i+1}]\} \\ &\quad = \binom{tZ-Z-1}{t-1} \cdot (\frac{1}{Z})^t \cdot (\frac{Z-1}{Z})^{((t-1)\cdot Z-t)} \\ &\quad = \binom{tZ-Z-1}{t-1} \cdot \frac{(Z-1)^{(tZ-Z-t)}}{Z^{(tZ-Z)}}. \end{aligned} \tag{12}$$

6.3 Complexity Analysis

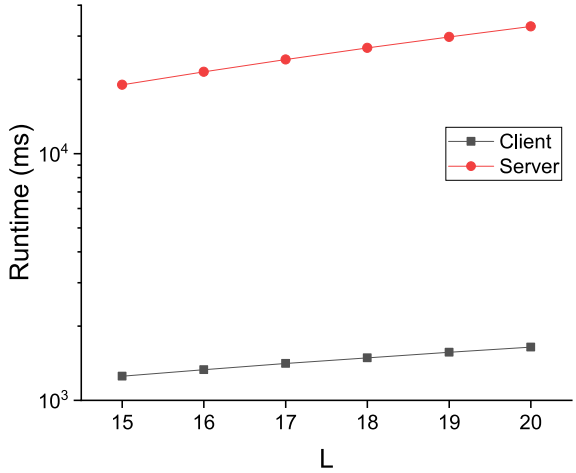
We discuss the complexity of the proposed mobile cloud storage system in semi-honest cloud setting and malicious cloud setting, respectively.

6.3.1 Semi-Honest Cloud Setting

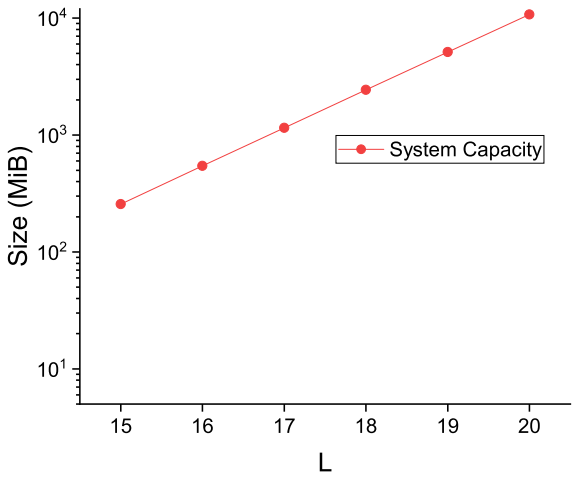
Our mobile cloud storage scheme is based on the AHE cryptosystem, i.e., Damgård-Jurik cryptosystem [35]. In our construction, ciphertexts are encrypted into three layers at most. Therefore, the ciphertext expansion is constant. Without loss of generality, we can just set the first encryption layer as 1. Suppose that the Damgård-Jurik cryptosystem encrypts a message of length γ bits. Then we have the parameters of the Damgård-Jurik cryptosystem are $|n| = \gamma$, $|p| = |q| = \gamma/2$. Each encrypted coefficient of the encrypted selection and update vector is 4γ. Consider there are $L+1$ coefficients in one encrypted vector, the size of the encrypted selection and update vector is $\Theta(\gamma L)$. Therefore, the item size should be $\Omega(\gamma L) = \Omega(\gamma \log N)$. We also have the total capacity of mobile cloud storage system is $\Omega(N \cdot$



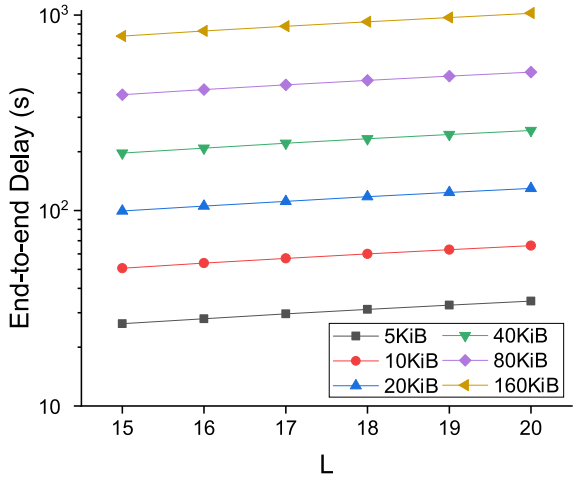
(a) Minimum effective item size and communication cost



(b) Runtime (minimum effective item size)



(c) Storage capacity (minimum effective item size)



(d) End-to-end delay (item size = 5KiB to 160 KiB)

Fig. 9. The performance results.

TABLE 3
Performances of *Per Access* on 1 GiB Database

	Minimum effective item (block) size	Client comp.	Cloud comp.	Communication
Onion ORAM	1.20 MiB	25 min	$>$ 3.5 days	7.4 MiB
C-ORAM	82.98 KiB	25.82 s	72 min	2.59 MiB
Ours	4.50 KiB	1.41 s	24.09 s	57.8 KiB

$\gamma L)$ bits, the maximum size of position map is $\Omega(N(L + \log L)) = \Omega(NL)$ bits and the size of the stash is $\Omega(t \cdot Z \cdot \gamma L)$.

6.3.2 Malicious Cloud Setting

The main different in malicious cloud setting is that the client has to download encrypted verification chunks for each bucket on the access path. Suppose that there are ν verification chunks for each encrypted item, and the code rate of the Reed-Solomon code is α (< 1).ss According to [20], the malicious cloud has at most $(\frac{1+\alpha}{2})^{\nu}$ probability to successfully learn information of access request. Therefore, the item size should be $\Omega(\nu\gamma L)$ to achieve constant bandwidth communication.

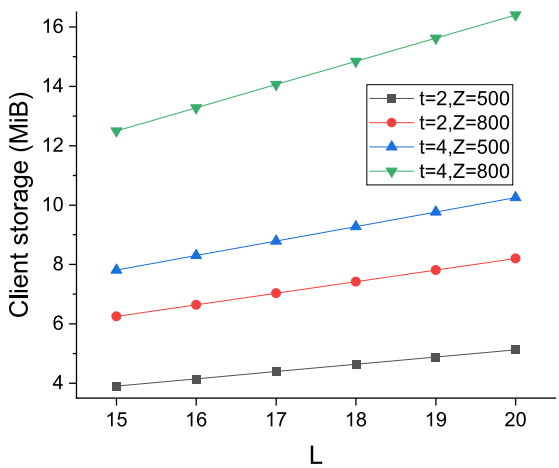
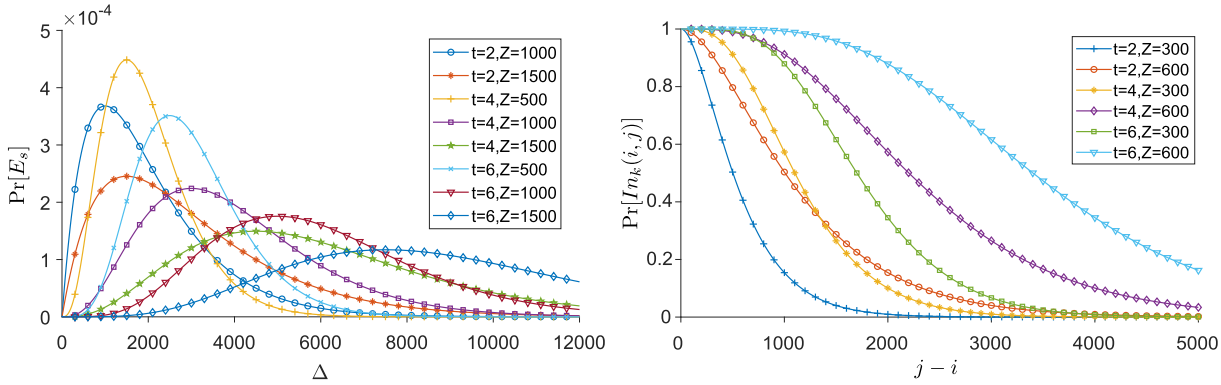


Fig. 10. The client storage (minimum effective item size).

7 Implement and Evaluation

We first compare the proposed mobile cloud storage scheme with other two oblivious random access machine



(a) The probability $\Pr[E_s]$ (b) The probability $\Pr[In_k(i,j)]$

Fig. 11. The probability analysis results.

schemes, which also have constant communication bandwidth overhead, i.e., Onion ORAM [20] and C-ORAM [34]. The comparison is shown in the Table 2. Since there are omitted large constants in Onion ORAM and C-ORAM, our scheme has significantly smaller item (block) size than other two schemes.

Then we implement the proposed mobile cloud storage scheme with Java and conduct the evaluation environment with workstations to simulate the client and the cloud, respectively. The workstations are all installed with Ubuntu 16.06 LTS system with 3.4 GHz Intel Core i5-7500 processor. For security, we set the parameters of AHE scheme with $|p| = |q| = 1024$ and $|n| = 2048$. We also partially implement Onion ORAM and C-ORAM and set parameters of Onion ORAM and C-ORAM following [41]. Specifically, the real block number of a bucket and the eviction factor are both set as 333 and λ is set as 80. All experiments are run in four-threaded method and semi-honest setting. The Table 3 indicates the performances of *per access* in three schemes on a reasonable database (1 GiB). Due to the smaller item size and constant parameters, our scheme is much more efficient than Onion ORAM and C-ORAM in terms of client computation, cloud computation and communication. Since the runtime of Onion ORAM is enormous, the experimental results of Onion ORAM are estimated based on the evaluation performances of core operations in Onion ORAM. In our evaluation environment, even in the best case and omitting the amortized cost of eviction, the cloud computation of per access in Onion ORAM still takes about 3.5 days. Note that, if we repeatedly run access operation 18 times in our scheme to retrieve same size data (81 KiB) as in C-ORAM, our scheme has almost the same client computation overhead (25.38 s) as the C-ORAM scheme, but the cloud computation overhead is still much smaller than C-ORAM, i.e., about 10 times smaller.

We also fully estimate our MCS scheme as shown in Fig. 9. Fig. 9a indicates the minimum effective item size and the communication cost (per access) of our construction. It is easy to conclude that the communication cost is linear with the minimum effective item size and our construction achieves constant communication bandwidth overhead. Fig. 9b indicates the performances of our scheme in terms of client computation and cloud computation respectively with minimum effective item size. Since the minimum effective item size of our construction is extremely small, the client's runtime could be less than 2 seconds while $L = 15$ to 20. Fig. 9c shows that the mobile cloud storage capacity with minimum effective item size while $L = 15$ to 20. From this figure, we can easily know that our construction can support reasonable capacity by conducting the value of L. Our construction supports variable item sizes by setting different the chunk numbers to meet variable kinds of application requirements. Fig. 9d indicates the end-to-end delay of our construction with item size as 5 KiB to 160 KiB in a 100 *Mbps* LAN setting.[7]

Furthermore, we evaluate the client storage and the probability $\Pr[E_s]$ of the event E_s with different parameters. The Fig. 10 indicates the client storage requirement whiling the variable stash parameters with the minimum effective item size. The Fig. 11a indicates the probability $\Pr[E_s]$ of the event E_s. Combining the two figures and the Fig. 9c, we can have that the propose mobile cloud storage scheme allows the client to consume small local storage and gain a much larger mobile cloud storage with high-level privacy preservation. The Fig. 11b indicates the probability $\Pr[In_k(i,j)]$, i.e., the probability that an item k is still in the stash during the jth access after first being visited in the ith access ($j > i$). From the figure, it is easy to know that if the difference $j - i$ is fixed, the probability $\Pr[In_k(i,j)]$ increases with the size of the stash.

8 Conclusion

In this paper, we propose an efficient, secure and privacy-preserving mobile cloud storage (MCS). The proposed scheme can protect data and access pattern simultaneously. Compared with existing schemes, our scheme has smaller item size, lightweight client-side computation and constant communication overhead. We also take temporal locality into consideration to further improve the efficiency of the scheme. By combining additional method, our scheme can be verifiable to resist malicious cloud. As a building block of the proposed MCS scheme, we also present an oblivious selection and update protocol, in which a client can

7. The minimum item size is slightly larger than 5 KiB when $L = 20$. We just set the item size as 5 KiB by reducing the chunk number of items in this situation.

obliviously select and update its encrypted data items outsourced in the cloud with small vectors. Due to small client computation and communication, we believe this protocol may be of independent interest for other secure multi-party computation application scenarios. The security and privacy proofs and analyses show that our scheme achieves data confidentiality and privacy preservation. Finally, we compare our scheme with other two oblivious storage schemes and fully estimate our construction in a simulation environment. The results indicate that our scheme is significantly efficient and has good performances.

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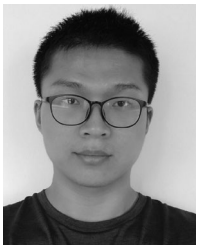

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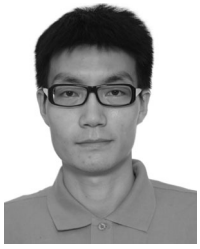

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