

# Enabling Public Verifiability and Data Dynamics for Storage Security in Cloud Computing

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**Abstract.** Cloud Computing has been envisioned as the next-generation architecture of IT Enterprise. It moves the application software and databases to the centralized large data centers, where the management of the data and services may not be fully trustworthy. This unique paradigm brings about many new security challenges, which have not been well understood. In this work, we study the problem of ensuring the integrity of data storage in Cloud Computing. In particular, we consider the task of allowing a third party auditor (TPA), on behalf of the cloud client, to verify the storage correctness of the dynamic data stored in the cloud. The introduction of TPA eliminates the involvement of client through the auditing of whether his data stored in the cloud is indeed intact, which can be important in achieving economies of scale for Cloud Computing. The support to handle dynamic data via the most general forms of data operation, such as block modification, insertion and deletion, is also a significant step toward practicality, since services in Cloud Computing are not limited to archive or backup data only. While prior works on ensuring remote data integrity often lacks the support of either public verifiability or dynamic data operations, we achieve them both. We identify the difficulties and potential security problems of direct extensions with fully dynamic data updates from prior works and show how to construct an elegant verification scheme for seamless integration of these two salient features in our protocol design. In particular, to achieve efficient data dynamics, we improve the Proof of Retrievability model [1] by manipulating the classic Merkle Hash Tree (MHT) construction for block tag authentication. Extensive security and performance analysis show that the proposed scheme is highly efficient and proven secure in the strongest security model.

## 1 Introduction

Several trends are opening up the era of Cloud Computing, which is an Internet-based development and use of computer technology. The ever cheaper and more powerful processors, together with the “software as a service” (SaaS) computing architecture, are transforming data centers into pools of computing service on a huge scale. Meanwhile, the increasing network bandwidth and reliable yet flexible network connections make it even possible that clients can now subscribe high quality services from data and software that reside solely on remote data centers.

Although envisioned as a promising service platform for the Internet, this new data storage paradigm in “Cloud” brings about many challenging design issues which have profound influence on the usability, reliability, scalability, security, and performance of the overall system. One of the biggest concerns with cloud data storage is that of data integrity verification at untrusted servers. For example, the storage service provider, which experiences Byzantine failures occasionally, may decide to hide the data errors from the clients for the benefit of their own. What is more serious is that for saving money and storage space the service provider might neglect to keep or deliberately delete rarely accessed data files which belong to an ordinary client. Consider the large size of the outsourced electronic data and the client’s constrained resource capability, the core of the problem can be generalized as how can the client find an efficient way to perform periodical integrity verifications without the local copy of data files.

In order to solve this problem, many schemes are proposed under different system and security models [1–11]. In all these works, great efforts are made to design solutions that meet various

requirements: high scheme efficiency, stateless verifier, unbounded use of queries and retrievability of data, etc. Considering the role of the verifier in the model, all the schemes presented before fall into two categories: private verifiability and public verifiability. Although schemes with private verifiability can achieve higher scheme efficiency, public verifiability allows anyone, not just the client (data owner), to challenge the cloud server for correctness of data storage while keeping no private information. Then, clients are able to delegate the evaluation of the service performance to an independent third party auditor (TPA), without devotion of their computation resources. In the cloud, the clients themselves are unreliable or cannot afford the overhead of performing frequent integrity checks. Thus, for practical use, it seems more rational to equip the verification protocol with public verifiability, which is expected to play a more important role in achieving economies of scale for Cloud Computing. In addition, for the efficiency concern, data integrity verification should be conducted in a blockless manner [12]. That is, the outsourced data themselves should not be required by the verifier for the verification purpose. In the context of public verification, the importance of blocklessness goes even further because an TPA should not be allowed to possess the original data files for the obvious security concern.

Another major concern among previous designs is that of supporting dynamic data operation for cloud data storage applications. In Cloud Computing, the remotely stored electronic data might not only be accessed but also updated by the clients, e.g., through block modification, deletion, insertion etc. Unfortunately, the state-of-the-art in remote data storage studies mainly focus on static data files and the importance of this dynamic data updates has received limited attention in the data possession applications so far [1–4, 6, 11, 13]. Moreover, as will be shown later, the direct extension of the current PDP or PoR schemes to support data dynamics may lead to security loopholes. Although there are many difficulties faced by researchers, it is well believed that supporting dynamic data operation can be of vital importance to the practical application of storage outsourcing services. In view of the key role of public verifiability and the supporting of data dynamics for cloud data storage, in this paper we present a framework and an efficient construction for seamless integration of these two components in our protocol design. Our contribution can be summarized as follows:

- We propose a general formal PoR model with public verifiability for cloud data storage, in which both blockless and stateless verification are achieved simultaneously.
- We equip the proposed PoR construction with the function of supporting for fully dynamic data operations, especially to support block insertion, which is missing in most existing schemes.
- We prove the security of our proposed construction and justify the performance of our scheme through concrete implementation and comparisons with the state-of-the-art.

## 1.1 Related Work

Recently, much of growing interest has been pursued under remotely stored data verification studies [1–11, 14, 15]. Ateniese *et al.* [2] define the “provable data possession” (PDP) model for ensuring possession of files on untrusted storages. In their scheme, they utilize RSA-based homomorphic tags for auditing outsourced data, thus can provide public verifiability. However, Ateniese *et al.* do not consider the case of dynamic data storage, and the direct extension of their scheme from static data storage to dynamic case brings many design and security problems. In their subsequent work [13], Ateniese *et al.* propose a dynamic version of the prior PDP scheme. However, the system imposes a priori bound on the number of queries and does not support fully dynamic data operations, i.e., it only allows very basic block operations with limited functionality and the real block insertions cannot be supported. In [14], Wang *et al.* consider dynamic data storage in distributed scenario, and the proposed challenge-response protocol can both determine the data correctness and locate possible errors. Similar to [13], they only consider partial support for dynamic data operation.

Juels *et al.* [3] describe a “proof of retrievability” (PoR) model and give a more rigorous proof of their scheme. In this model, spot-checking and error-correcting codes are used to ensure both “possession” and “retrievability” of data files on archive service systems. Specifically, some special blocks called “sentinels” are randomly embedded into the data file  $F$  for detection purpose and

$F$  is further encrypted to protect the positions of these special blocks. However, like the PDP scheme, the number of queries a client can perform is also a fixed priori and the introduction of pre-computed “sentinels” prevents the development or success of realizing dynamic data updates. In addition, public verifiability is not supported in their scheme.

Shacham *et al.* [1] design an improved PoR scheme with full proofs of security in the strongest security model defined in [3]. Like the construction in [2], they use publicly verifiable homomorphic authenticators that are built from BLS signatures and proven secure in the random oracle model. Based on the elegant BLS construction, public retrievability is achieved and the proofs can be aggregated into a small authenticator value. Still the authors only consider static data files.

Erway *et al.* [12] was the first to explore constructions for dynamic provable data possession. They extend the PDP model in [2] to support provable updates to stored data files using rank-based authenticated skip lists. This scheme is essentially a fully dynamic version of the PDP solution. In particular, to support updates, especially for block insertion, they try to eliminate the index information in the “tag” computation in Ateniese’s PDP model [2]. To achieve this, before the verification procedure, they employ authenticated skip list data structure to authenticate the tag information of challenged or updated blocks first. However, the efficiency of their scheme remains in question. In their construction, server has to keep a 4-tuple state information  $A(v_i)$  for each node in the skip list structure, and any update to the stored file  $F$ , even few blocks, will result in the inevitable updates of rank and interval information of all nodes along the path from the updated blocks to the top leftmost node, thus introducing large computational complexity. Oprea *et al.* [9] propose and evaluate the constructions for protecting the integrity of files in cryptographic file systems. They use Merkle hash tree to authenticate the original data blocks with constant-size trusted storage and consider the update, append and delete operations. However, in their scheme, the problem of how to realize block insertion is not explicitly discussed and public verifiability is not considered.

In our solution, we propose an efficient remote data verification scheme with public verifiability and fully dynamic data operation support for PoR systems. The verifier can conduct periodical checks without retrieving the original outsourced data files, thus blockless verification is achieved. Furthermore, index information in the computation of block signatures are eliminated and the classic data structure-Merkle hash tree is used for authentication of block tag information instead of original data files. We formally prove the security of our construction and provide detailed performance evaluation.

**Organization.** The rest of the paper is organized as follows. In section 2, we define the system model, security model and our goal. Then, we present our scheme in section 3 and provide security analysis in section 4. We further analyze the experiment results and show the practicality of our schemes in section 5. Finally, we conclude in section 6.

## 2 Problem Statement

### 2.1 System Model

A representative network architecture for cloud data storage is illustrated in Fig. 1. Three different network entities can be identified as follows:

- Client: an entity, which has large data files to be stored in the cloud and relies on the cloud for data maintenance and computation, can be either individual consumers or organizations.
- Cloud Storage Server (CSS): an entity, which is managed by Cloud Service Provider (CSP), has significant storage space and computation resource to maintain clients’ data.
- Third Party Auditor (TPA): a TPA, which has expertise and capabilities that clients do not have, is trusted to assess and expose risk of cloud storage services on behalf of the clients upon request.

In the cloud paradigm, by putting the large data files on the remote servers, the clients can be relieved of the burden of storage and computation. As clients no longer possess their data locally,

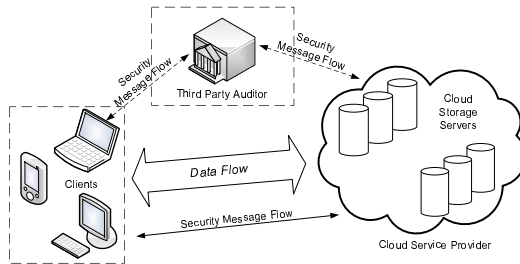


Fig. 1: Cloud data storage architecture

it is of critical importance for the clients to ensure that their data are being correctly stored and maintained. That is, clients should be equipped with certain security means so that they can periodically verify the correctness of the remote data even without the existence of local copies. In case that clients do not necessarily have the time, feasibility or resources to monitor their data, they can delegate the monitoring task to a trusted TPA of their respective choices.

In this paper, we only consider verification schemes with public verifiability: any TPA in possession of the public key can act as a verifier. We assume that TPA is unbiased while the server is untrusted. We also assume that the point-to-point communication channels among the cloud servers, the clients and the TPA are authenticated and reliable, which can be achieved in practice with little overhead. Note that we don't address the issue of data privacy in this paper, as the topic of data privacy in Cloud Computing is orthogonal to the problem we study here.

For application purposes, the clients may interact with the cloud servers via CSP to access or retrieve their pre-stored data. More importantly, in practical scenarios the client may frequently perform block-level operations on the data files. The most general forms of these operations we consider in this paper are modification, insertion, and deletion.

## 2.2 Security Model

Shacham and Waters propose a security model for PoR system in [1]. Generally, the checking scheme is secure if (i) there exists no efficient algorithm that can cheat the verifier with non-negligible probability; (ii) there exists a polynomial-time extractor that can recover the original data file by carrying out multiple challenges-responses. Under the definition of this PoR system, the client can periodically challenge the storage server to ensure the correctness of the cloud data and the original files can be recovered by interacting with the server. The authors in [1] also defines the correctness and soundness of PoR scheme: the scheme is correct if the verification algorithm accepts when interacting with the valid prover (e.g., the server returns a valid response) and it is sound if any cheating server that convinces the client it is storing the data file is actually storing that file. Note that in the “game” between the adversary and the client, the adversary has full access to the information stored in the server, i.e., the adversary can play the part of the prover (server). In the verification process, the adversary's goal is to cheat the client successfully, i.e., trying to generate valid responses and pass the data verification without being detected. We say that the adversary (cheating server) is  $\epsilon$ -admissible if it convincingly answers an  $\epsilon$ -fraction of verification challenges.

Our security model has subtle but crucial difference from that of the original PoRs in the verification process. Note that the original PoR schemes [1, 3, 4, 16] do not consider dynamic data operations and the block insert cannot be supported at all. This is because the construction of the signatures is involved with the file index information  $i$ . Thus, once a file block is inserted, the computation overhead is unacceptable since the signatures of all the file blocks should be re-computed with the new indexes. To deal with this limitation, we remove the index information  $i$  in generating the signatures and use  $H(m_i)$  as the tag for block  $m_i$  (see section 3.3) instead of  $H(\text{name}||i)$  [1] or  $h(v||i)$  [3], so individual data operation on any file block will not affect the

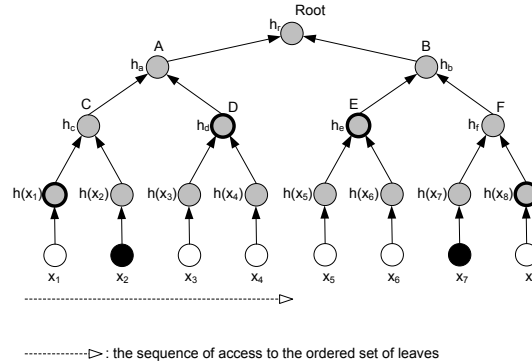


Fig. 2: Merkle hash tree authentication of data elements. We treat the leaf nodes  $h(x_1), \dots, h(x_n)$  as the left-to-right sequence.

others. Recall that  $H(\text{name}||i)$  or  $h(v||i)$  should be generated by the client in the verification process [1, 2]. However, in our new construction the client without the data information has no capability to calculate  $H(m_i)$ . In order to successfully perform the verification while achieving blockless, the server should take over the job of computing  $H(m_i)$  and then return it to the prover. The consequence of this variance will lead to a serious problem: it will give the adversary more opportunities to cheat the prover by manipulating  $H(m_i)$  or  $m_i$ . Due to this construction, our security model differs from that of the original PoR in both the verification and the data updating process. Specifically, in our scheme tags should be authenticated in each protocol execution other than calculated or pre-stored by the verifier (The details will be shown in section 3). Note that in this paper, we will use server and prover (or client, TPA and verifier) interchangeably in this paper.

### 2.3 Design Goals

Our design goals can be summarized as the following: (1) Public verification for storage correctness assurance: to allow anyone, not just the clients who originally stored the file on cloud servers, to have the capability to verify the correctness of the stored data on demand; (2) Dynamic data operation support: to allow the clients to perform block-level operations on the data files while maintaining the same level of data correctness assurance. The design should be as efficient as possible so as to ensure the seamless integration of public verifiability and dynamic data operation support; (3) Blockless verification: no challenged file blocks should be retrieved by the verifier (e.g., TPA) during verification process for both efficiency and security concerns. (4) Stateless verification: to eliminate the need for state information maintenance at the verifier side between audits throughout the long term of data storage.

## 3 The Proposed Scheme

We start with some notation and the definition of our scheme, followed by the construction details, enhancements and discussions on design considerations.

### 3.1 Notation and Preliminaries

**Bilinear Map.** A bilinear map is a map  $e : G \times G \rightarrow G_T$ , where  $G$  is a Gap Diffie-Hellman (GDH) group and  $G_T$  is another multiplicative cyclic group of prime order  $p$  with the following properties [17, 18]: (i) Computable: there exists an efficiently computable algorithm for computing  $e$ ; (ii) Bilinear: for all  $h_1, h_2 \in G$  and  $a, b \in \mathbb{Z}_p$ ,  $e(h_1^a, h_2^b) = e(h_1, h_2)^{ab}$ ; (iii) Non-degenerate:  $e(g, g) \neq 1$ , where  $g$  is a generator of  $G$ .

**Merkle Hash Tree.** A Merkle Hash Tree (MHT) is a well-studied authentication structure, which is intended to efficiently and securely prove that a set of elements are undamaged and unaltered. It is constructed as a binary tree where the leaves in the MHT are the hashes of authentic data values. Fig. 2 depicts an example of authentication. The verifier with the authentic  $h_r$  requests for  $\{x_2, x_7\}$  and requires the authentication of the received blocks. The prover provides the verifier with the auxiliary authentication information (AAI)  $\Omega_2 = \langle h(x_1), h_b \rangle$  and  $\Omega_7 = \langle h(x_8), h_e \rangle$ . The verifier can then verify  $x_2$  and  $x_7$  by first computing  $h(x_2)$ ,  $h(x_7)$ ,  $h_c = h(h(x_1)||h(x_2))$ ,  $h_f = h(h(x_7)||h(x_8))$ ,  $h_a = h(h_c||h_d)$ ,  $h_b = h(h_e||h_f)$  and  $h_r = h(h_a||h_b)$ , and then checking if the calculated  $h_r$  is the same as the authentic one. MHT is commonly used to authenticate the values of data blocks. However, in this paper we further employ MHT to authenticate both the values and the positions of data blocks. We treat the leaf nodes as the left-to-right sequence, so any leaf node can be uniquely determined by following this sequence and the way of computing the root in MHT.

### 3.2 Definition

In our scheme, both public verifiability and fully dynamic data operation are supported. We now show the definitions and parameters used in our construction.

$(pk, sk) \leftarrow \text{KeyGen}(1^k)$ . This probabilistic algorithm is run by the client. It takes as input security parameter  $1^k$ , and returns public key  $pk$  and private key  $sk$ .

$(\Phi, sig_{sk}(H(R))) \leftarrow \text{SigGen}(sk, F)$ . This algorithm is run by the client. It takes as input private key  $sk$  and a file  $F$  which is an ordered collection of blocks  $\{m_i\}$ , and outputs the signature set  $\Phi$ , which is an ordered collection of signatures  $\{\sigma_i\}$  on  $\{m_i\}$ . It also outputs metadata—the signature  $sig_{sk}(H(R))$  of the root  $R$  of a Merkle hash tree. In our construction, the leaf nodes of the Merkle hash tree are hashes of  $H(m_i)$ .

$(P) \leftarrow \text{GenProof}(F, \Phi, chal)$ . This algorithm is run by the server. It takes as input a file  $F$ , its signatures  $\Phi$ , and a challenge  $chal$ . It outputs a data integrity proof  $P$  for the blocks specified by  $chal$ .

$\{TRUE, FALSE\} \leftarrow \text{VerifyProof}(pk, chal, P)$ . This algorithm can be run by either the client or the third party auditor upon receipt of the proof  $P$ . It takes as input the public key  $pk$ , the challenge  $chal$ , and the proof  $P$  returned from the server, and outputs  $TRUE$  if the integrity of the file is verified as correct, or  $FALSE$  otherwise.

$(F', \Phi', P_{update}) \leftarrow \text{ExecUpdate}(F, \Phi, update)$ . This algorithm is run by the server. It takes as input a file  $F$ , its signatures  $\Phi$ , and an data operation request “update” from client. It outputs an updated file  $F'$ , updated signatures  $\Phi'$  and a proof  $P_{update}$  for the operation.

$\{(TRUE, sig_{sk}(H(R'))), FALSE\} \leftarrow \text{VerifyUpdate}(pk, update, P_{update})$ . This algorithm is run by the client. It takes as input public key  $pk$ , the signature  $sig_{sk}(H(R))$ , an operation request “update”, and its proof  $P_{update}$  from server. If the verification succeeds, it outputs a signature  $sig_{sk}(H(R'))$  for the new root  $R'$ , or  $FALSE$  otherwise.

### 3.3 Our Construction

The notion of public verifiability was first proposed by Ateniese et al. [2]. In their scheme, a linear combination of file blocks can be aggregated into a single block and verified by employing homomorphic property of RSA. Another scheme, which was proposed by Shacham et al. [1], can also achieve public verifiability while providing more compact homomorphic authenticators based on BLS signature. In our scheme, we use BLS as a basis to construct the proof-of-retrievability system. As will be shown, the pairing operation has more nice properties in building a PoR scheme and all the schemes designed under BLS can also be implemented in RSA construction. Notice that, both schemes mentioned above do not consider data updates, which is a very practical and important issue in cloud data storage. In discussion of section 3.4, we will show that direct extensions of previous work have various security problems and we believe that protocol design

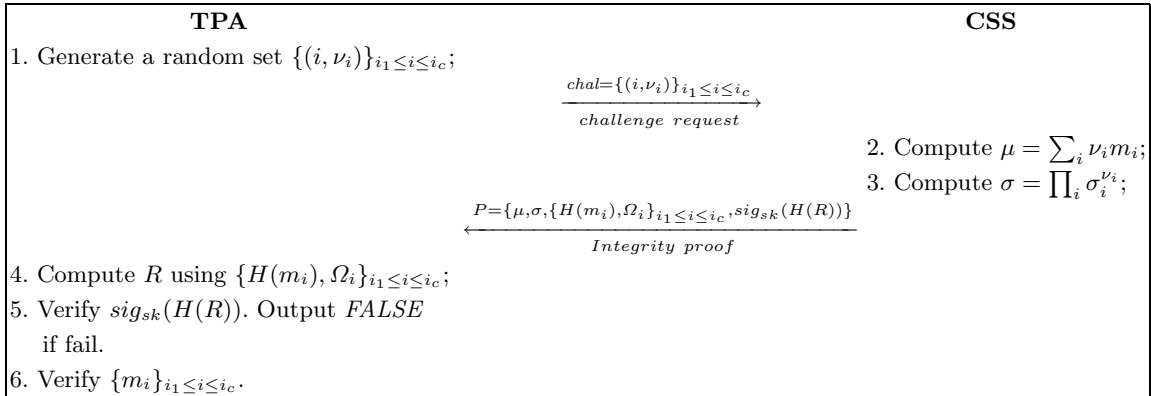


Fig. 3: Protocols for Default Integrity Verification

for supporting dynamic data operation is a major challenging and remaining problem for cloud storage systems.

Now we start to present the main idea behind our scheme. As in the previous PoR systems [1,3], we assume the client encodes the raw data file  $\tilde{F}$  into  $F$  using Reed-Solomon codes and divides the encoded file  $F$  into  $n$  blocks  $m_1, \dots, m_n$ <sup>3</sup>, where  $m_i \in \mathbb{Z}_p$  and  $p$  is a large prime. Let  $e : G \times G \rightarrow G_T$  be a bilinear map, with a hash function  $H : \{0, 1\}^* \rightarrow G$ , viewed as a random oracle [1]. Let  $g$  be the generator of  $G$ . The procedure of our protocol execution is as follows:

■ **Setup:** The client’s public key and private key are generated by invoking  $KeyGen(\cdot)$ . By running  $SigGen(\cdot)$ , the raw data file  $F$  are pre-processed and the homomorphic authenticators together with metadata are produced.

$KeyGen(1^k)$ . The client chooses a random  $\alpha \leftarrow \mathbb{Z}_p$  and computes  $v \leftarrow g^\alpha$ . The secret key is  $sk = (\alpha)$  and the public key is  $pk = (v)$ .

$SigGen(sk, F)$ . Given the encoded file  $F = (m_1, \dots, m_n)$ , the client chooses a random element  $u \leftarrow G$  and computes signature  $\sigma_i$  for each block  $m_i$  ( $i = 1, \dots, n$ )

$$\sigma_i \leftarrow (H(m_i) \cdot u^{m_i})^\alpha. \quad (1)$$

Denote the set of signatures by  $\Phi = \{\sigma_i\}, 1 \leq i \leq n$ . The client then generates a root  $R$  based on the construction of Merkle Hash Tree (MHT), where the leaf nodes of the tree are an ordered set of hashes of “file tags”  $H(m_i)$  ( $i = 1, \dots, n$ ), where  $H(m_i)$  is the BLS hash of block  $m_i$ . Next, the client signs the root  $R$  under the private key  $\alpha$ :  $sig_{sk}(H(R)) \leftarrow (H(R))^\alpha$ .

The client sends  $\{F, \Phi, sig_{sk}(H(R))\}$  to the server and deletes them from its local storage.

■ **Default Integrity Verification:** The client or the third party, e.g., TPA, can verify the integrity of the outsourced data by challenging the server. To generate the message “chal”, the TPA (verifier) picks a random  $c$ -element subset  $I = \{i_1, \dots, i_c\}$  of set  $[1, n]$ , and for each  $i \in I$  a random element  $\nu_i \leftarrow \mathbb{Z}_p$ . The message “chal” specifies the positions of the blocks that are required to be checked in this challenge phase. The verifier sends the *chal*  $\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}$  to the prover (server).

$GenProof(F, \Phi, chal)$ . Upon receiving challenge  $chal = \{(i, \nu_i)\}_{i_1 \leq i \leq i_c}$ , the server computes

$$\mu = \sum_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \nu_i m_i \in \mathbb{Z}_p \quad (2)$$

and

$$\sigma = \prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \sigma_i^{\nu_i} \in G. \quad (3)$$

<sup>3</sup> We assume these blocks are distinct with each other.

In addition, the prover will also provide the verifier with a small amount of auxiliary information  $\{\Omega_i\}_{i_1 \leq i \leq i_c}$ , which are the node siblings on the path from the leaves  $\{h(H(m_i))\}_{i_1 \leq i \leq i_c}$  to the root  $R$  of the MHT. The prover responds the verifier with proof  $P = \{\mu, \sigma, \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, sig_{sk}(H(R))\}$ .  $VerifyProof(pk, chal, P)$ . Upon receiving the responses from the prover, the verifier generates root  $R$  using  $\{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}$  and authenticates it by checking  $e(sig_{sk}(H(R)), g) \stackrel{?}{=} e(H(R), g^\alpha)$ . If the authentication fails, the verifier rejects by emitting *FALSE*. Otherwise, the verifier checks

$$e(\sigma, g) \stackrel{?}{=} e\left(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} H(m_i)^{\nu_i} \cdot u^\mu, v\right). \quad (4)$$

If so, output *TRUE*; otherwise, output *FALSE*. The protocol is illustrated in Fig. 3.

■ **Dynamic Data Operation with Integrity Assurance:** Dynamic data operation can be very important to the practical application of cloud storage services. Clients are, of course, more inclined to operate on dynamic files other than static ones. However, most previous schemes apply to static files or support only partial data updates (e.g., append operation). The support of fully data dynamics means that all general operations, including data modification, data insertion and data deletion, are all supported. We will use  $\mathcal{M}, \mathcal{I}, \mathcal{D}$  to denote these operations. Now we show how our scheme can explicitly and efficiently handle fully dynamic data operations for cloud data storage. Note that in the following descriptions for the protocol design of dynamic operation, we assume that the file  $F$  and the signature  $\Phi$  have already been generated and properly stored at server. The root metadata  $R$  has been signed by the client and stored at the cloud server, so that anyone who has the client's public key can challenge the correctness of data storage.

-**Data Modification:** We start from data modification, which is one of the most frequently used operations in cloud data storage. A basic data modification operation refers to the replacement of specified blocks with new ones.

Suppose the client wants to modify the  $i$ -th block  $m_i$  to  $m'_i$ . The protocol procedures are described in Fig. 4. At start, based on the new block  $m'_i$ , the client generates the corresponding signature  $\sigma'_i = (H(m'_i) \cdot u^{m'_i})^\alpha$ . Then, he constructs an *update request* message “*update* =  $(\mathcal{M}, i, m'_i, \sigma'_i)$ ” and sends to the server, where  $\mathcal{M}$  denotes the modification operation. Upon receiving the request, the server runs  $ExecUpdate(F, \Phi, update)$ . Specifically, the server (i) replaces the block  $m_i$  with  $m'_i$  and outputs  $F'$ ; (ii) replaces the  $\sigma_i$  with  $\sigma'_i$  and outputs  $\Phi'$ ; (iii) replaces  $H(m_i)$  with  $H(m'_i)$  in the Merkle hash tree construction and generates the new root  $R'$  (see the example in Fig. 5). Finally, the server responds the client with a proof for this operation,  $P_{update} = (\Omega_i, H(m_i), sig_{sk}(H(R)), R')$ , where  $\Omega_i$  is the AAI for authentication of  $m_i$ .

After receiving the proof for modification operation from server, the client first generates root  $R$  using  $\{\Omega_i, H(m_i)\}$  and authenticates the AAI or  $R$  by checking  $e(sig_{sk}(H(R)), g) \stackrel{?}{=} e(H(R), g^\alpha)$ . If it is not true, output *FALSE*, otherwise the client can now check whether the server has performed the modification as required or not, by further computing the new root value using  $\{\Omega_i, H(m'_i)\}$  and comparing it with  $R'$ . If it is not true, output *FALSE*, otherwise output *TRUE*. Then, the client signs the new root metadata  $R'$  by  $sig_{sk}(H(R'))$  and sends it to the server for update.

-**Data Insertion:** Compared to data modification, which does not change the logic structure of client's data file, another general form of data operation, data insertion, refers to inserting new blocks after some specified positions in the data file  $F$ .

Suppose the client wants to insert block  $m^*$  after the  $i$ -th block  $m_i$ . The protocol procedures are similar to the data modification case (see Fig. 4, now  $m'_i$  can be seen as  $m^*$ ). At start, based on  $m^*$  the client generates the corresponding signature  $\sigma^* = (H(m^*) \cdot u^{m^*})^\alpha$ . Then, he constructs an *update request* message “*update* =  $(\mathcal{I}, i, m^*, \sigma^*)$ ” and sends to the server, where  $\mathcal{I}$  denotes the insertion operation. Upon receiving the request, the server runs  $ExecUpdate(F, \Phi, update)$ . Specifically, the server (i) stores  $m^*$  and adds a leaf  $h(H(m^*))$  “after” leaf  $h(H(m_i))$  in the Merkle hash tree and outputs  $F'$ ; (ii) adds the  $\sigma^*$  into the signature set and outputs  $\Phi'$ ; (iii) generates the new root  $R'$  based on the updated Merkle hash tree. Finally, the server responds the client with a proof for this operation,  $P_{update} = (\Omega_i, H(m_i), sig_{sk}(H(R)), R')$ , where  $\Omega_i$  is the AAI for authentication of  $m_i$  in the old tree. An example of block insertion is illustrated in Fig. 6, to insert



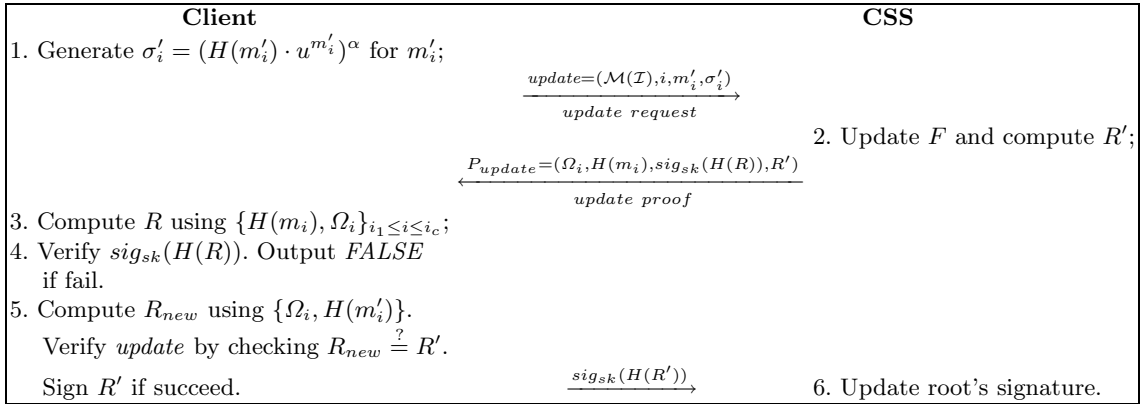


Fig. 4: The protocol for provable data update (Modification and Insertion)

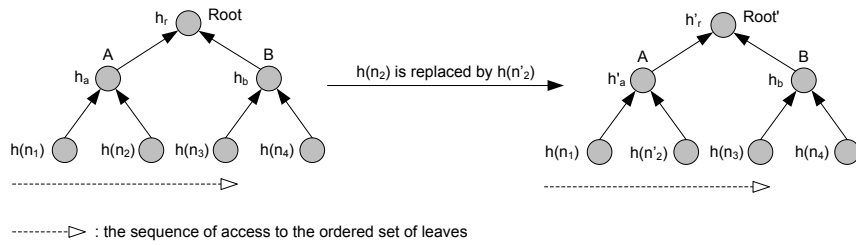


Fig. 5: Example of MHT update under block modification operation. Here,  $n_i$  and  $n'_i$  are used to denote  $H(m_i)$  and  $H(m'_i)$ , respectively.

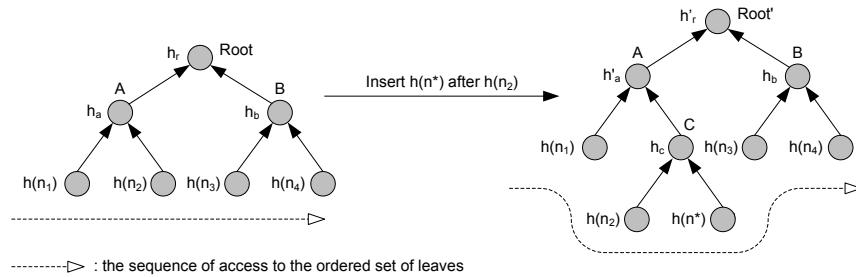


Fig. 6: Example of MHT update under block insertion operation. Here,  $n^*$  is used to denote  $H(m^*)$ .

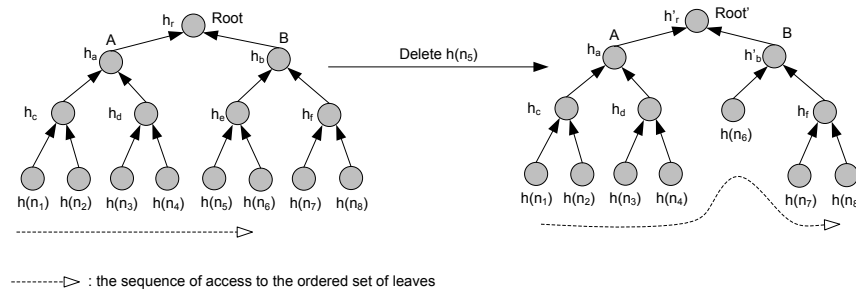


Fig. 7: Example of MHT update under block deletion operation.

$h(H(m^*))$  after leaf node  $h(H(m_2))$ , only node  $h(H(m^*))$  and an internal node  $C$  is added to the original tree, where  $h_c = h(h(H(m_2)) || h(H(m^*)))$ .

After receiving the proof for insert operation from server, the client first generates root  $R$  using  $\{\Omega_i, H(m_i)\}$  and authenticates the AAI or  $R$  by checking if  $e(\text{sig}_{sk}(H(R)), g) = e(H(R), g^\alpha)$ . If it is not true, output *FALSE*, otherwise the client can now check whether the server has performed the insertion as required or not, by further computing the new root value using  $\{\Omega_i, H(m_i), H(m^*)\}$  and comparing it with  $R'$ . If it is not true, output *FALSE*, otherwise output *TRUE*. Then, the client signs the new root metadata  $R'$  by  $\text{sig}_{sk}(H(R'))$  and sends it to the server for update.

**-Data Deletion:** Data deletion is just the opposite operation of data insertion. For single block deletion, it refers to deleting the specified block and moving all the latter blocks one block forward. Suppose the server receives the *update* request for deleting block  $m_i$ , it will delete  $m_i$  from its storage space, delete the leaf node  $h(H(m_i))$  in the MHT and generate the new root metadata  $R'$  (see the example in Fig. 7). The details of the protocol procedures are similar to that of data modification and insertion, which are thus omitted here.

■ **The Enhancement for Multi-client Verification:** As cloud servers may concurrently handle multiple verification sessions from different clients, given  $K$  signatures on  $K$  distinct data files from  $K$  clients, it is more advantageous to aggregate all these signatures into a single one and verify it at one time. We can extend our scheme to allow for provable data updates and verification in a multi-client system. The key idea is to use the bilinear aggregate signature scheme [17], which has the following property: for any  $u_1, u_2, v \in G$ ,  $e(u_1 u_2, v) = e(u_1, v) \cdot e(u_2, v)$  and for any  $u, v \in G$ ,  $e(\psi(u), v) = e(\psi(v), u)$ . As in the BLS scheme, the aggregate signature scheme allows the creation of signatures on arbitrary distinct messages. Assume there are  $K$  clients in the system, and each client  $k$  has data files  $F_i = (m_{k,1}, \dots, m_{k,n})$ , where  $k \in \{1, \dots, K\}$ . For a particular client  $k$ , pick random  $x_k \leftarrow \mathbb{Z}_p$ , and compute  $v_k = g^{x_k}$ . The client's public key is  $v_k \in G$  and the public key is  $v_k \in \mathbb{Z}_p$ . In the *SigGen* phase, given the file  $F_k = (m_{k,1}, \dots, m_{k,n})$ , client  $k$  chooses a random element  $u_k \leftarrow G$  and computes signature  $\sigma_{k,i} \leftarrow [H(m_{k,i}) \cdot u_k^{m_{k,i}}]^{x_k} \in G$ . In the *challenge* phase, the verifier sends the query  $Q = \{(i, \nu_i)\}_{i_1 \leq i \leq i_c}$  to the prover (server) for verification of all  $K$  clients. In the *GenProof* phase, upon receiving the *chal*, for each client  $k$  ( $k \in \{1, \dots, K\}$ ), the prover computes  $\mu_k = \sum_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \nu_i m_{k,i} \in \mathbb{Z}_p$  and  $\sigma = \prod_{k=1}^K (\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \sigma_{k,i}^{\nu_i}) = \prod_{k=1}^K (\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} [H(m_{k,i}) \cdot u_k^{m_{k,i}}]^{x_k \nu_i})$ . The prover then responds the verifier with  $\{\sigma, \{\mu_k\}_{1 \leq k \leq K}, \{\Omega_{k,i}\}, \{H(m_{k,i})\}\}$ . In the *VerifyProof* phase, similar as the single client case, the verifier first authenticates tags  $H(m_{k,i})$  by verifying signatures on the roots (for each client's file). If the authentication succeeds, then, using the properties of the bilinear map, the verifier can check if the following equation holds:

$$e(\sigma, g) = \prod_{k=1}^K e\left(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} [H(m_{k,i})]^{\nu_i} \cdot (u_k)^{\mu_k}, v_k\right). \quad (5)$$

This establishes the validity of the scheme. The proof of security of this scheme is similar to the multi-client case, thus omitted here.

### 3.4 Discussion on Design Considerations

**Instantiations based on BLS and RSA.** As discussed above, we present an BLS-based construction that offers both public verifiability and data dynamics. In fact, our proposed scheme can also be constructed based on RSA signatures. Compared with RSA construction [2, 12], as a desirable benefit, the BLS construction can offer shorter homomorphic signatures (e.g., 160 bits) than those use RSA techniques (e.g., 1024 bits). In addition, the BLS construction has the shortest query and response (we does not consider AAI here): 20 bytes and 40 bytes [1]. However, while BLS construction is not suitable to use variable sized blocks (e.g., for security parameter  $\lambda = 80$ ,  $m_i \in \mathbb{Z}_p$ , where  $p$  is a 160-bit prime), the RSA construction can support variable sized blocks. The reason is that in RSA construction the order of  $QR_N$  is unknown to the server, so it is impossible to find distinct  $m_1$  and  $m_2$  such that  $g^{m_1} \bmod N = g^{m_2} \bmod N$  according to the factoring assumption. But the block size cannot increase without limit, as the verification block

$\mu = \sum_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \nu_i m_i$  grows linearly with the block size. Recall that  $h(H(m_i))$  are used as the MHT leaves, upon receiving the challenge the server can calculate these tags on-the-fly or pre-store them for fast proof computation. We note that, one can directly use  $h(g^{m_i})$  as the MHT leaves instead of  $h(H(m_i))$ . In this way at the verifier side the job of computing the aggregated signature  $\sigma$  should be accomplished after authentication of  $g^{m_i}$ . Now the computation of aggregated signature  $\sigma$  is eliminated at the server side, as a trade-off, additional computation overhead may be introduced at the verifier side.

**Support for Data Dynamics.** The direct extension of PDP or PoR schemes to support data dynamics may have security problems. We take PoR for example, the scenario in PDP is similar. When  $m_i$  is required to be updated,  $\sigma_i = [H(\text{name}||i)u^{m_i}]^x$  should be updated correspondingly. Moreover,  $H(\text{name}||i)$  should also be updated, otherwise by dividing  $\sigma_i$  by  $\sigma'_i$ , the adversary can obtain  $[u^{\Delta m_i}]^x$  and use this information and  $\Delta m_i$  to update any block and its corresponding signature for arbitrary times while keeping  $\sigma$  consistent with  $\mu$ . This attack cannot be avoided unless  $H(\text{name}||i)$  is changed for each update operation. Also, because the index information is included in computation of the signature, an insertion operation at any position in  $F$  will cause the updating of all individual signatures. To eliminate the attack mentioned above and make the insertion efficient, as we have shown, we use  $H(m_i)$  instead of  $H(\text{name}||i)$  as the block tags, and the problem of supporting fully dynamic data operation is remedied in our construction. Note that different from the public information  $\text{name}||i$ ,  $m_i$  is no longer known to client after the outsourcing of original data files. Since the client or TPA cannot compute  $H(m_i)$ , this job has to be assigned to the server (prover). However, by leveraging the advantage of computing  $H(m_i)$ , the prover can cheat the verifier through the manipulation of  $H(m_i)$  and  $m_i$ . For example, suppose the prover wants to check the integrity of  $m_1$  and  $m_2$  at one time. Upon receiving the challenge, the prover can just compute the pair  $(\sigma, \mu)$  using arbitrary combinations of two blocks in the file. Now the response formulated in this way can successfully pass the integrity check. So, to prevent this attack, we should first authenticate the tag information before verification, i.e., ensuring these tags are corresponding to the blocks to be checked.

**Designs for Blockless and Stateless Verification.** The naive way of realizing data integrity verification is to make the hashes of the original data blocks as the leaves in MHT, so the data integrity verification can be conducted without tag authentication and signature aggregation steps. However, this construction, which requires the server to return all the challenged blocks for authentication, does not provide an efficient way to realize data dynamics. Moreover, due to concern for security in the context of public verification, the TPA should not be allowed to possess the original outsourced data for verification purpose. To overcome these deficiencies, most existing works in remote data checking adopt a blockless strategy for data integrity verification. For the same reason, this paper adopts the blockless approach, and we authenticate the block tags instead of original data blocks in the verification process. As we have described, during the *setup* phase the verifier signs the metadata  $R$  and stores it together with its signature on the server. Thus, when performing data updates or verification, the server should return the signature and some auxiliary information in the Merkle hash tree for verification purpose. At the verifier side, the verifier have to re-compute  $R$  and authenticate it. Actually, one can reduce the communication complexity by storing the root  $R$  on the verifier, i.e.,  $R$  can be seen as public information and the client should distribute the root information to TPA in the setup phase. However, this makes the verifier “stateful” in some sense since TPA will store this frequently updated information for the rest of time. So there is a tradeoff between the communication overhead and the purpose of keeping fully stateless.

## 4 Security Analysis

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

**Definition 1. (CDH Problem)** *The Computational Diffie-Hellman problem is that, given  $g, g^x, g^y \in \mathbb{G}$  for unknown  $x, y \in \mathbb{Z}_p$ , to compute  $g^{xy}$ .*

We say that the  $(t, \epsilon)$ -CDH assumption holds in  $\mathbb{G}_1$  if no  $t$ -time algorithm has the non-negligible probability  $\epsilon$  in solving the CDH problem.

A proof-of-retrievability protocol is sound if any cheating prover that convinces the verification algorithm that it is storing a file  $M$  is actually storing that file, which we define in saying that it yields up the file  $M$  to an extractor algorithm which interacts with it using the proof-of-retrievability protocol. We formalize the notion of an extractor and then give a precise definition for soundness.

**Theorem 1.** *If the signature scheme is existentially unforgeable and the computational Diffie-Hellman problem is hard in bilinear groups, no adversary against the soundness of our public-verification scheme could cause verifier to accept in a proof-of-retrievability protocol instance with non-negligible probability, except by responding with correctly computed values.*

*Proof.* It is easy to prove that the signature scheme is existentially unforgeable with the assumption that BLS [18] short signature scheme is secure. In concrete, assume there is a secure BLS signature scheme, with public key  $y = g^\alpha$  and a map-to-point hash function  $H$ . If there is an adversary that can break our signature scheme, we show how to use this adversary to forge a BLS signature as follows: Set  $u = g^{x_0}$  by choosing  $x_0$  from  $Z_p$ . For any signature query on message  $m$ , we can submit this message to BLS signing oracle and get  $\sigma = H(m)^\alpha$ . Therefore, the signing oracle of this new signature scheme can be simulated as  $\sigma' = \sigma y^m = (H(m)g^{mx_0})^\alpha$ . Finally, if there is any adversary can forge a new signature  $\sigma' = (H(m')u^{m'})^\alpha$  on message  $m'$  that has never been queried, then, we can get a forged BLS signature on message  $m'$  as  $\sigma' = \sigma / y^{m'x_0} = H(m')^\alpha$ . This completes the proof of the new signature scheme is secure if the BLS signature scheme is secure.

We then prove the theorem by using a sequence of games. The first game, Game 0, is simply the challenge game described in adversary model, which is also similar to [1], with the changes for public verifiability sketched. Game 1 is the same as Game 0, with one difference. The challenger keeps a list of all signed tags ever issued as part of a store-protocol query. If the adversary ever submits a tag either in initiating a proof-of-retrievability protocol or as the challenge tag, the challenger will abort if it is a valid tag that has never been signed by the challenger. Based on the definition of Game 0 and Game 1, it is obviously that we can use the adversary to construct a forger against the signature scheme, if there is a difference in the adversary's success probability between Games 0 and 1.

Game 2 is the same as Game 1, except that in Game 2, the challenger keeps a list of its responses to queries from the adversary. Now the challenger observes each instance of the proof-of-retrievability protocol with the adversary. Let the expected response that would have been obtained from an honest prover be  $P = \{\mu, \sigma, \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, sig_{sk}(H(R))\}$ . The correctness of  $H(m_i)$  can be verified through  $\{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}$  and  $sig_{sk}(H(R))$ . The correctness of the proof can be verified based on the following equation  $e(\sigma, g) = e(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} H(m_i)^{\nu_i} \cdot u^\mu, v)$ . Assume the adversary's response is  $P'$ . Because of the authentication in MHT, the second part in  $P'$  should be the same with  $\{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}$  and  $sig_{sk}(H(R))$ . Suppose the adversary's response is  $P' = \{\mu', \sigma', \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, sig_{sk}(H(R))\}$ . The verification of  $(\mu', \sigma')$  is  $e(\sigma', g) = e(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} H(m_i)^{\nu_i} \cdot u^{\mu'}, v)$ . Obviously,  $\mu' \neq \mu$ , otherwise,  $\sigma' = \sigma$ , which contradicts our assumption in this game. Define  $\Delta\mu = \mu' - \mu$ . With this adversary, the simulator could break the challenge CDH instance: Given  $(g, g^\alpha, h) \in G$ , the simulator is asked to output  $h^\alpha$ . The simulator sets  $v = g^\alpha$  and  $u = g^a h^b$  for  $a, b \in Z_p^*$ . The simulator could answer the signature query with similar method as described in [1], by letting  $H(m_i) = g^{r_i} h^{-m_i}$ . Finally, the adversary outputs  $P' = \{\mu', \sigma', \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, sig_{sk}(H(R))\}$ . We obtain  $e(\sigma' / \sigma, g) = e(u^{\Delta\mu}, v) = e((g^a h^b)^{\Delta\mu}, g^\alpha)$ . From this equation, we have  $e(\sigma' \sigma^{-1} v^{a\Delta\mu}, g) = e(h, v)^{b\Delta\mu}$ . Therefore,  $h^\alpha = (\sigma' \sigma^{-1} v^{a\Delta\mu})^{\frac{1}{b\Delta\mu}}$  because  $v = g^\alpha$ . To analyze the probability that the challenger aborts in the game, we only need to compute the probability that  $b\Delta\mu = 0 \pmod p$ . Because  $b$  is chosen by the challenger and hidden from the adversary, the probability that  $b\Delta\mu = 0 \pmod p$  will be only  $1/p$ , which is negligible.

Game 3 is the same as Game 2, with the following difference: As before, the challenger observes proof-of-retrievability protocol instances. Suppose the file that causes the abort is that the signa-

tures are  $\{\sigma_i\}$ . Suppose  $Q = (i, v_i)_{i_1 \leq i \leq i_c}$  is the query that causes the challenger to abort, and that the adversary's response to that query was  $P' = \{\mu', \sigma', \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, \text{sig}_{sk}(H(R))\}$ . Let the expected response obtained from an honest prover be  $P = \{\mu, \sigma, \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, \text{sig}_{sk}(H(R))\}$ . We have proved in Game 2 that  $\sigma = \sigma'$ . It is only the values  $\mu$  and  $\mu'$  that can differ. Define  $\Delta\mu = \mu' - \mu$ . The simulator answers the adversary's queries. Finally, The adversary outputs a forged signature  $P' = \{\mu', \sigma', \{H(m_i), \Omega_i\}_{i_1 \leq i \leq i_c}, \text{sig}_{sk}(H(R))\}$ . We have  $e(\sigma', g) = e(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} H(m_i)^{\nu_i} \cdot u^{\Delta\mu}, v) = e(\sigma, g) = e(\prod_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} H(m_i)^{\nu_i} \cdot u^{\mu}, v)$ . From this equation, we have  $1 = u^{\Delta\mu}$ . In this case,  $\Delta\mu = 0 \pmod p$ . Therefore, we have  $\mu = \mu' \pmod p$ .

As we analyzed above, there is only negligible difference probability between these games. This completes the proof.

**Theorem 2.** *Suppose a cheating prover on an  $n$ -block file  $F$  is well-behaved in the sense above, and that it is  $\epsilon$ -admissible. Let  $\omega = 1/\#B + (\rho n)^\ell / (n - c + 1)^c$ . Then, provided that  $\epsilon - \omega$  is positive and non-negligible, it is possible to recover a  $\rho$ -fraction of the encoded file blocks in  $O(n/(\epsilon - \rho))$  interactions with cheating prover and in  $O(n^2 + (1 + \epsilon n^2)(n)/(\epsilon - \omega))$  time overall.*

*Proof.* The verification of the proof-of-retrievability is similar with [1], due to space limitation, we omit the details of the proof here. The difference in our work is to replace  $H(i)$  with  $H(m_i)$  such that secure update can still be realized without including the index information. These two types of tags are used for the same purpose (i.e., to prevent potential attacks), so this change will not affect the extraction algorithm defined in the proof-of-retrievability. We can also prove that extraction always succeeds against a well-behaved cheating prover, with the same probability analysis given in [1].

**Theorem 3.** *Given a fraction of the  $n$  blocks of an encoded file  $F$ , it is possible to recover the entire original file  $F$  with all but negligible probability.*

*Proof.* Based on the rate- $\rho$  Reed-Solomon codes, this result can be easily derived, since any  $\rho$ -fraction of encoded file blocks suffices for decoding.

## 5 Performance Analysis

We list the features of our proposed scheme in Table 1 and make a comparison of our scheme and state-of-the-art techniques. The DPDP scheme [12] extends the original PDP [2] to support data dynamics using authenticated skip list. Both schemes are based on RSA construction and do not consider the retrievability of data files. Our scheme, which is based on BLS signature, is an extension of the PoR model [1] to achieve fully data dynamics. For the sake of completeness, we implemented both our BLS and RSA-based instantiations as well as the state-of-the-art scheme [12] in Linux. Our experiment is conducted using C on a system with an Intel Core 2 processor running at 2.4 GHz, 768 MB RAM, and a 7200 RPM Western Digital 250 GB Serial ATA drive with an 8 MB buffer. Algorithms (pairing, SHA1 etc.) are implemented using the Pairing-Based Cryptography (PBC) library version 0.4.18 and the crypto library of OpenSSL version 0.9.8h. To achieve 80-bit security parameter, the curve group we work on has a 160-bit group order and the size of modulus  $N$  is 1024 bits. All results are the averages of 10 trials. Table 2 lists the performance metrics for 1 GB file under various erasure code rate  $\rho$  while maintaining high detection probability (99%) of file corruption. In our schemes, rate  $\rho$  denotes that any  $\rho$ -fraction of the blocks suffices for file recovery as proved in Theorem 3, while in [12], rate  $\rho$  denotes the tolerance of file corruption. According to [2, 14], if  $t$  fraction of the file is corrupted, by asking proof for a constant  $c$  blocks of the file, the verifier can detect this server misbehavior with probability  $p = 1 - (1 - t)^c$ . Let  $t = 1 - \rho$  and we get the variant of this relationship  $p = 1 - \rho^c$ . Under this setting, we quantify the extra cost introduced by the support of dynamic data in our scheme into server computation, verifier computation as well as communication overhead. Note that for fair comparison, several efficiency techniques have been applied to all the three schemes. All the listed computation time does not include the I/O bound.

Metric \ Scheme	Scheme				
	[2]	[1]	[13]*	[12]	Our Scheme
Data dynamics	No		Yes		
Public verifiability	Yes	Yes	No	No <sup>†</sup>	Yes
Sever computation complexity	$O(1)$	$O(1)$	$O(1)$	$O(\log n)$	$O(\log n)$
Verifier computation complexity	$O(1)$	$O(1)$	$O(1)$	$O(\log n)$	$O(\log n)$
Communication complexity	$O(1)$	$O(1)$	$O(1)$	$O(\log n)$	$O(\log n)$
Verifier storage complexity	$O(1)$	$O(1)$	$O(1)$	$O(1)$	$O(1)$

Table 1: Comparisons of different remote data integrity checking schemes. The security parameter  $\lambda$  is eliminated in the costs estimation for simplicity. \* The scheme only supports bounded number of integrity challenges and partially data updates, i.e., data insertion is not supported. <sup>†</sup> No explicit implementation of public verifiability is given for this scheme.

Metric \ Rate- $\rho$	Our BLS-Based instantiation		Our RSA-Based instantiation		[12]
	99%	97%	99%	97%	99%
Sever computation time (ms)	6.52	2.29	13.42	4.76	13.80
Verifier computation time (ms)	1154.39	503.88	794.27	208.28	807.90
Communication cost (KB)	243	80	223	76	280

Table 2: Performance comparison under different tolerance rate  $\rho$  of file corruption for 1GB file. The block size for RSA-based instantiation and scheme in [12] is chosen to be 4KB.

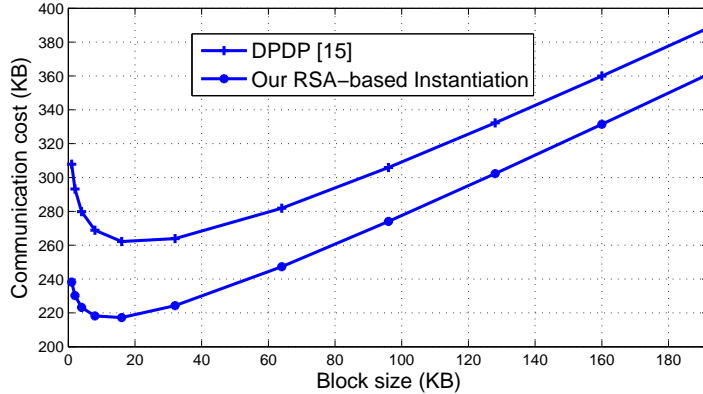


Fig. 8: Comparison of communication complexity between our RSA-based instantiation and DPDP [12], for 1 GB file with variable block sizes. The detection probability is maintained to be 99%.

From table 2, it can be observed that the overall performance of the three schemes are comparable to each other. Due to the smaller block size (i.e., 20bytes), our BLS-based instantiation is more than 2 times faster than the other two in terms of server computation time. However, it has larger computation cost at the verifier side as the paring operation in BLS consumes more time than RSA techniques. Note that the communication cost of DPDP scheme is the largest among the three in practice. This is because there are 4-tuple values associated with each skip list node for one proof, which results in extra communication cost as compared to our constructions. The communication overhead (server’s response to the challenge) of our RSA-based instantiation and DPDP scheme [12] under different block sizes is illustrated in Fig. 8. We can see that the

communication cost grows almost linearly as the block size increases, this is mainly caused by the increasing in size of the verification block  $\mu = \sum_{\{(i, \nu_i)\}_{i_1 \leq i \leq i_c}} \nu_i m_i$ . However, at very small block sizes (less than 20KB), both schemes can achieve an optimal point that minimizes the total communication cost.

## 6 Conclusion

To ensure cloud data storage security, it is critical to enable a third party auditor (TPA) to evaluate the service quality from an objective and independent perspective. Public verifiability also allows clients to delegate the integrity verification tasks to TPA while they themselves can be unreliable or not be able to commit necessary computation resources performing continuous verifications. Another major concern is how to construct verification protocols that can accommodate *dynamic* data files. In this paper, we explored the problem of providing simultaneous public verifiability and data dynamics for remote data integrity check in cloud computing. Our construction is deliberately designed to meet these two important goals while efficiency being kept closely in mind. We extended the PoR model [1] by using an elegant Merkle hash tree construction to achieve fully dynamic data operation. Experiments show that our construction is efficient in supporting fully dynamic data operation with provable verification.

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