Efficient Public Integrity Checking for Cloud Data Sharing with Multi-User Modification

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***Abstract*—In past years a body of data integrity checking techniques have been proposed for securing cloud data services. Most of these works assume that only the data owner can modify cloud-stored data. Recently a few attempts started considering more realistic scenarios by allowing multiple cloud users to modify data with integrity assurance. However, these attempts are still far from practical due to the tremendous computational cost on cloud users. Moreover, collusion between misbehaving cloud servers and revoked users is not considered. This paper proposes a novel data integrity checking scheme characterized by multi-user modification, collusion resistance and a constant computational cost of integrity checking for cloud users, thanks to our novel design of polynomial-based authentication tags and proxy tag update techniques. Our scheme also supports public checking and efficient user revocation and is provably secure. Numerical analysis and extensive experimental results show the efficiency and scalability of our proposed scheme.**

I. Introduction

The continuous development of cloud techniques has boosted a number of cloud-based applications. In particular, more and more applications are using cloud as a collaboration platforms, in which data are not only persisted in cloud for storage but also subject to frequent modifications from multiple users. Real-world examples are cloud-based synchronization platforms such as Dropbox for Business [1] and Sugarsync [2], which enable multiple team members to work in sync, accessing and modifying the same file on cloud servers anywhere anytime. For correct execution of this kind of cloud-based collaborative applications, one problem is to assure data integrity, i.e., each data modification operation is indeed performed by an authorized group member and the data remains intact thereafter. This problem is important given the fact that cloud platforms, even well-known cloud platforms, may experience hardware/software failures, human errors and malicious attacks [3], [4].

Related Work. In order to ensure the integrity of data stored on remote/cloud servers, a series of solutions have been proposed based on various techniques [5], [6], [7], [8], [9], [10], [11], [12], [13]. However, most of these existing solutions only consider the case of single writer – only the data owner who holds secret keys can modify the data. If these solutions are trivially extended to support multiple writers with data integrity assurance, the data owner has to stay online, collecting modified data from other users and regenerating authentication tags for them. Obviously, this kind of trivial extension will introduce a tremendous workload to the data owner, especially in scenarios with a large number of writers (users) and/or a high frequency of data modification operations. To allow multiple users to modify data, Wang et al. [14] proposed a public integrity auditing scheme using ring signature-based homomorphic authenticators. Nevertheless, in ref. [14] user revocation is not considered and the auditing cost is linear to the group size and data size. In order to further enhance the previous works, another attempt was made by Wang et al, [13]. However, ref. [13] still suffers from a non-trivial computational cost which is linear to the group size and the number of checking tasks, and thus is limited in scalability. In addition, user revocation in ref. [13] is based on the assumption that no collusion occurs between cloud servers and revoked user. As a matter of fact, collusion between invalid users and cloud servers in ref. [13] will lead to the disclosure of secrets of all other valid users. To our best knowledge, there still lacks an efficient and publicly verifiable integrity checking scheme for cloud data sharing that supports multiple writers with secure user revocation.

Challenges. To solve this open problem, the following major (not necessarily complete list of) challenges exist: 1) *efficiency and scalability*. The main difficulty is attributed to two facets - on one hand, each data block (assuming data integrity is verified per block) shall have its own authentication tag; on the other hand, each writer (user) needs to generate a separate authentication tag, which is necessary for integrity checking, for each data block that he/she has modified. Consequently, the communication/computational complexity for integrity checking can grow linearly with the number of writers and/or the number of data blocks being checked. 2) *efficient and secure user revocation*. User revocation is a challenging issue in most security systems and usually involves disabling user secret keys. For efficient user revocation, one technique is to delegate the task to the cloud by disclosing partial secret to cloud servers. This method, however, leaves it a challenging issue to detect misbehaving cloud servers who collude with unauthorized users. 3) *public checking*. In practical systems, data integrity checking can be performed not only by data owners or writers but also by a third-party auditor or any general user who needs to access the data.

Our Contributions. In this work, we address the above challenges and propose an efficient public integrity checking scheme for cloud data sharing that supports multiple writers. Our proposed scheme is featured by public integrity checking and constant computational cost on the user side, thanks to our

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novel design on polynomial-based authentication tags which allows aggregation of tags of different data blocks. For system scalability, we further empower the cloud with the ability to aggregate authentication tags from multiple writers into one when sending the integrity proof information to the verifier. As a result, just a constant size of integrity proof information needs to be transmitted to the verifier no matter how many data blocks are being checked and how many writers are associated with the data blocks. Moreover, our novel design allows secure delegation of user revocation operations to the cloud even if cloud servers collude with malicious users. Last but not least, our proposed scheme allows aggregation of integrity checking operations for multiple tasks (files) through our batch integrity checking technique. We prove the security of our design based on the Computational Diffie-Hellman (CDH) problem, the Bilinear Diffie-Hellman (BDH) problem and the t-Strong Diffie-Hellman (t-SDH) problem. Thorough analysis and extensive experimental results on Amazon EC2 demonstrate the scalability and efficiency of our design. Our contributions are summarized as follows,

- Our proposed scheme is among the first that achieves public integrity checking for cloud data sharing supporting multiple writers. Different from existing solutions, our scheme is efficient, highly scalable, and collusion resistant.
- Our novel design of authentication tags can serve as an independent tool that can easily find application in other related scenarios such as verifiable keyword search.
- We fully implemented our scheme and evaluated its performance through both numerical analysis and experimental results. The security of our design is proved.

The rest of this paper is organized as follows: In Section.II, we introduce the system model and threat model of our scheme. Section.III provides our detail construction, which is followed by the security analysis in Section.IV. The performance evaluation of our scheme is presented in Section.V. Section.VI introduces applications that can use our proposed solution. We conclude this paper in Section.VII.

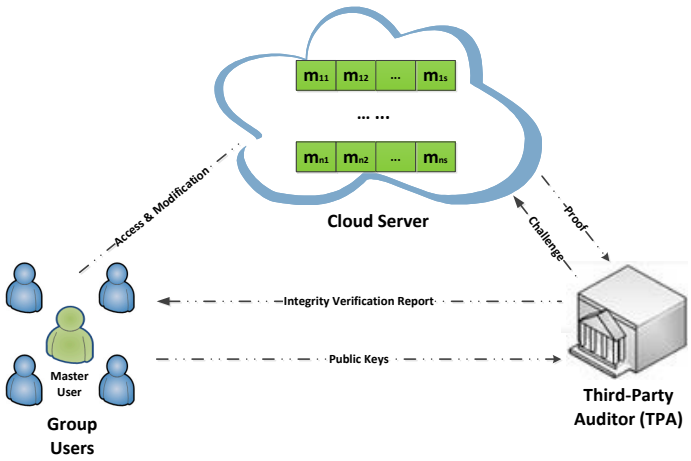

Fig. 1. System Model

II. Models and Assumptions

A. System Models

We consider a cloud system composed of three major entities as shown in Fig.1: the *cloud server*, *group users* and the *third-party auditor* (TPA). The cloud server is the party that provides data storage services to group users. Group users consist of a number of general users and a *master user*, who is the owner of the shared data and manages the membership of other group users. All group users can access and modify data. The TPA refers to any party that checks the integrity of data being stored on the cloud. As our proposed scheme allows public integrity checking, the *TPA can actually be any cloud user as long as he/she has access to the public keys*. In our design, data can be uploaded/created by either the master user or other group users. We assume data are stored in form of files which are further divided into a number of blocks. For integrity checking, each data block is attached with an authentication tag that is originally generated by the master user. When a user adds or modifies a block, he/she (the user) updates the corresponding authentication tag with his/her own secret key without contacting the master user.

B. Security Models

In this work we consider the following factors that may impact data integrity: 1) hardware/software failures and operational errors of system administrator; 2) external adversaries that corrupts data stored on the cloud; 3) revoked users who no longer have data access privilege but try to illegally modify data. We assume the cloud server to be curious but honest – the cloud server will follow the protocol but try to disclose the private information (e.g. users' secret keys) as much as possible. Different from previous work, we allow collusion between the cloud server and revoked group users. Since valid users are always allowed to modify data, we assume that they never collude with the cloud servers for corrupting data. However, the cloud and the valid users may collude with revoked users for helping them retain the modification privilege or impersonate other valid users (for generating tags). Therefore, our *security goals* are defined as follows: 1) if the data are corrupted, the cloud servers are not able to produce valid integrity proof information; 2) collusion among the cloud and any group users other than the master user will not give users any chance to forge authentication on behave of other users. In particular, revoked users shall not be able to impersonate valid users and generate legitimate tags by collusion attacks.

III. Our Scheme

A. Overview

In our scheme, there are K users u_k, $0 \leq k \leq K-1$ in a group sharing data stored on cloud and u_0 is the master user. u_0 is also the owner of data and manages the membership of the group. Therefore, u_0 can revoke any other group users when necessary. All users in the group can access and modify data stored on cloud. Specifically, our scheme consists of 7 algorithms: $\{KeyGen, Setup, Update, Challenge, Prove, Verify, User\ Revocation\}$. In the $KeyGen$ procedure, the master user u_0 generates public keys and master keys for the system, and

other group users generate secret keys for themselves. Then, u_0 processes files for storage in the $Setup$ procedure and generates the corresponding authentication tags. To modify the data stored on cloud, any group user u_k can run the $Update$ algorithm without the help of the master user u_0. The TPA can use the $Challenge$ algorithm to challenge the cloud and let it show the proof that it actually stores the data correctly by running the $Prove$ algorithm. With proof information and public keys, the TPA can verify the integrity of data stored on cloud using the $Verify$ algorithm. When a user leaves the group or misbehavior of a user is detected, the master user u_0 runs the $User\ Revocation$ algorithm to revoke the user.

B. Scheme Description

In this section, we describe the design details of each algorithm. Let $H(\cdot)$ denote the one-way hash function [15], G be a multiplicative cyclic group of prime order q, g and u be two random generators of G. $e : G \times G \rightarrow G_1$ is a bilinear map that has the properties of bilinearity, computability and non-degeneration. F is a file to be outsourced to cloud and is split into n blocks, and each block has s elements: $\{F_{ij}\}, 1 \leq i \leq n, 0 \leq j \leq s-1$. $f_{\vec{a}(x)}$ denotes a polynomial with coefficient vector $\vec{a} = (a_0, a_1, \cdots, a_{s-1}), a_j \in Z_q^*$.

KeyGen: Each user $u_k, 0 \leq k \leq K-1$ in the group first randomly chooses $\epsilon_k \leftarrow Z_q^*$ and generates $\nu = g^{\alpha\epsilon_0}$, $\kappa_k = g^{\epsilon_k}$. For group users $u_k, 1 \leq k \leq K-1$, they also generate $g^{\frac{1}{\epsilon_k}}$ and send $g^{\frac{1}{\epsilon_k}}$ to the master user u_0. Then, the master user u_0 computes $(g^{\frac{1}{\epsilon_k}})^{\epsilon_0} = g^{\frac{\epsilon_0}{\epsilon_k}}$. u_0 also randomly chooses $\alpha \leftarrow Z_q^*$ and generates $\{g^{\alpha^j}\}, 0 \leq j \leq s+1$. The public keys (PK), master keys (MK) of the system and secret keys (SK) of users are:

$$PK = \{g, u, q, \nu, \{g^{\alpha^j}\}_{0\leq j\leq s+1}, \{\kappa_k, g^{\frac{\epsilon_0}{\epsilon_k}}\}_{0\leq k\leq K-1}\}$$
$$MK = \{\epsilon_0, \alpha\}$$
$$SK_k = \{\epsilon_k\}_{1\leq k\leq K-1}$$

Setup: To outsource a file F, the master user u_0 splits it into n data blocks, and each block has s elements: $\{m_{ij}\}, 1 \leq i \leq n, 0 \leq j \leq s-1$. Then, u_0 generates authentication tag σ_i for each data block as:

$$\sigma_i = (u^{B_i} \cdot \prod_{j=0}^{s-1} g^{m_{ij}\alpha^{j+2}})^{\epsilon_0} = (u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)})^{\epsilon_0} \quad (1)$$

where $\vec{\beta_i} = \{0, 0, \beta_{i,0}, \beta_{i,1}, \cdots, \beta_{i,s-1}\}$ and $\beta_{i,j} = m_{i,j}$. $B_i = H(\{z_i||t_i||0\})$, z_i is the index of m_i, $t_i = H(m_i)$ and 0 is the user index of the master user. u_0 uploads data blocks and the corresponding authentication tags σ_i to cloud, and also sends B_i to the TPA (in practical implementation B_i can be first uploaded to cloud and later on downloaded by TPA).

Update: Suppose a group user $u_k, k \neq 0$ modifies a data block m_i to m_i'. He computes the tag for m_i' with his own secret key ϵ_k as:

$$\sigma_i' = (u^{B_i'} \cdot \prod_{j=0}^{s-1} g^{m'_{ij}\alpha^{j+2}})^{\epsilon_k} = (u^{B_i'} \cdot g^{f_{\vec{\beta'_i}}(\alpha)})^{\epsilon_k} \quad (2)$$

where $\vec{\beta_i'} = \{0, 0, \beta_{i,0}', \beta_{i,1}', \cdots, \beta_{i,s-1}'\}$ and $\beta_{i,j}' = m_{i,j}'$. $B_i' = H(\{z_i||t_i'||k\})$. User u_k uploads m_i' and σ_i' to cloud and sends B_i' to the TPA (in practical implementation B_i' can be first uploaded to cloud and later on downloaded by TPA). The cloud and/or TPA can verify whether these tags are indeed updated by u_k through checking the following:

$$e(u^{B_i'}, \kappa_k) \cdot e(g^{f_{\vec{\beta_i'}}(\alpha)}, \kappa_k) \stackrel{?}{=} e(\sigma_i', g) \quad (3)$$

Challenge: To challenge the cloud for data integrity checking, the TPA first randomly chooses d data blocks as a set D (We will discuss the size of set D in Section. III-D). Suppose the chosen d blocks are collectively modified by a set of C users, $0 \leq |C| \leq K-1$. The TPA generates two random numbers R, μ and produces $X = (g^{\frac{\epsilon_0}{\epsilon_k}})^R$, where $k \in C$ (TPA is aware of the set C by looking at B_i and/or B_i'). Finally, the TPA produces the challenging message $CM = \{D, X, g^R, \mu\}$ and sends it to the cloud.

Prove: On receiving the challenging message $CM = \{D, X, g^R, \mu\}$, the cloud first generates $\{p_i = \mu^i \ mod\ q\}, i \in D$. The cloud also computes $y = f_{\vec{A}}(\mu) \ mod\ q$, where $\vec{A} = \{0, 0, \sum_{i\in D} p_i m_{i,0}, \cdots, \sum_{i\in D} p_i m_{i,s-1}\}$. Then, the cloud divides the polynomial $f_{\vec{A}}(x) - f_{\vec{A}}(\mu)$ with $(x-\mu)$ using polynomial long division, and denotes the coefficients vector of the resulting quotient polynomial as $\vec{w} = (w_0, w_1, \cdots, w_{s+1})$, that is, $f_{\vec{w}}(x) \equiv \frac{f_{\vec{A}}(x) - f_{\vec{A}}(\mu)}{x-\mu}$. With $\vec{w}$, the cloud generates

$$\psi = \prod_{j=2}^{s+1} (g^{\alpha^j})^{w_j} = g^{f_{\vec{w}}(\alpha)} \quad (4)$$

Afterward, for data blocks in challenged set D modified by user $u_k, k \in C$, the cloud computes

$$\pi_i = e(\sigma_i, g^{\frac{\epsilon_0 R}{\epsilon_k}}) = e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{\epsilon_0 R} \quad (5)$$

For those blocks not modified or modified by u_0, the cloud computes

$$\pi_i = e(\sigma_i, g^R) = e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{\epsilon_0 R} \quad (6)$$

π_i will be aggregated as $\pi = \prod_{i\in D} \pi_i^{p_i}$.

Finally, the cloud responds the TPA with proof information $Prf = \{\pi, \psi, y\}$.

Verify: Based on the proof information Prf, the TPA verifies the integrity of file as

$$e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \stackrel{?}{=} \pi \cdot e(\kappa_0^{-y}, g^R) \quad (7)$$

where $\eta = u^\omega$ and $\omega = \sum_{i\in D} B_i p_i$. If Eq.7 holds, the TPA outputs the verification result $VerifyRst$ as $Accept$; otherwise, outputs $VerifyRst$ as $Reject$.

User Revocation: Whenever there is a user that need to be revoked, say $u_k, k \neq 0$, the master user u_0 will notify the cloud, valid group users and the TPA that u_k is revoked. On receiving the user revocation request, the cloud will update the authentication tags of blocks that were last modified by u_k as:

$$\begin{aligned} \sigma_i' &= e(\sigma_i, g^{\frac{\epsilon_0}{\epsilon_k}})^\rho \quad (8) \\ &= e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)})^{\epsilon_k}, g^{\frac{\epsilon_0}{\epsilon_k}})^\rho \\ &= e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{\epsilon_0 \rho} \end{aligned}$$

where ρ is a random number chosen by the cloud. On receiving the user revocation notification, the TPA will discard the public information $g^{\frac{\epsilon_0}{\epsilon_k}}$ and will no longer use it in the $Challenge$ algorithm. Let Rev denote the set of challenging data blocks that were last modified by the revoked user u_k. When the cloud runs the $Prove$ algorithm, it generates proof information π for data blocks in set $D \backslash Rev$ as:

$$\pi = \prod_{i \in D \backslash Rev} \pi_i^{p_i} \tag{9}$$

For those blocks in Rev, the cloud computes

$$\vartheta = \prod_{i \in Rev} e(\sigma_i', g)^{p_i} = \prod_{i \in Rev} e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{\epsilon_0 \rho p_i}$$

$$y = f_{\vec{A}}(\mu), \qquad f_{\vec{w}}(x) \equiv \frac{f_{\vec{A}}(x) - f_{\vec{A}}(\mu)}{x - \mu}$$

where $\vec{A} = \{0, 0, \sum_{i \in D \backslash Rev} m_{i,0} p_i \cdot \sum_{i \in Rev} m_{i,0} p_i \rho, \cdots, \sum_{i \in D \backslash Rev} m_{i,s-1} p_i \cdot \sum_{i \in Rev} m_{i,s-1} p_i \rho\}$. The cloud also generates $\psi = \prod_{j=2}^{s+1} (g^{\alpha^j})^{w_j} = g^{f_{\vec{w}}(\alpha)}$ and $\chi = u^{\rho}$, and sends the proof information back to the TPA as:

$$Prf = \{\pi, \vartheta, \psi, \chi\}$$

On receiving the proof information, the TPA first computes $\omega' = \sum_{i \in Rev} B_i p_i$ and $\omega'' = \sum_{i \in D \backslash Rev} B_i p_i$. Then, the TPA generates $\eta = \chi^{\omega'} \cdot u^{\omega''}$ and verifies the integrity as

$$e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \stackrel{?}{=} \pi \cdot e(\kappa_0^{-y}, g^R) \cdot \vartheta^R \tag{10}$$

If Eq.10 holds, the TPA outputs the verification result $VerifyRst$ as $Accept$; otherwise, outputs $VerifyRst$ as $Reject$.

Correctness: We analyze the correctness of our construction based on Eq.7 and Eq.10 as
Eq.7:

$$\begin{aligned} & e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \qquad (11) \\ &= e(u^{\sum_{i \in D} B_i}, g)^{R\epsilon_0} \cdot e(g^{f_{\vec{w}}(\alpha)}, g^{(\alpha - \mu)})^{R\epsilon_0} \\ &= \prod_{i \in D} e(u^{B_i}, g)^{R\epsilon_0} \cdot e(g^{f_{\vec{A}}(\alpha)}, g)^{R\epsilon_0} \cdot e(g^{-y}, g)^{R\epsilon_0} \\ &= \prod_{i \in D} e(u^{B_i}, g)^{R\epsilon_0} \cdot \prod_{i \in D} e(g^{f_{\vec{\beta_i}}(\alpha)}, g)^{R\epsilon_0} \cdot e(g^{-y}, g)^{R\epsilon_0} \\ &= \prod_{i \in D} e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{R\epsilon_0} \cdot e(g^{-y}, g)^{R\epsilon_0} \\ &= \pi \cdot e(\kappa_0^{-y}, g^R) \end{aligned}$$

Eq.10:

$$\begin{aligned} & e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \qquad (12) \\ &= e(u^{\sum_{i \in D} B_i}, g)^{R\epsilon_0} \cdot e(g^{f_{\vec{w}}(\alpha)}, g^{(\alpha - \mu)})^{R\epsilon_0} \\ &= \prod_{i \in D \backslash Rev} e(u^{B_i}, g)^{R\epsilon_0} \cdot \prod_{i \in Rev} e(u^{B_i}, g)^{R\rho\epsilon_0} \\ &\cdot e(g^{f_{\vec{A}}(\alpha)}, g)^{R\epsilon_0} \cdot e(g^{-y}, g)^{R\epsilon_0} \\ &= \prod_{i \in D \backslash Rev} e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{R\epsilon_0} \\ &\cdot \prod_{i \in Rev} e((u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}), g)^{R\rho\epsilon_0} \cdot e(\kappa_0^{-y}, g^R) \\ &= \pi \cdot e(\kappa_0^{-y}, g^R) \cdot \vartheta^R \end{aligned}$$

From Eq.11 and Eq.12, it is easy to see that our scheme is correct.

C. Efficient Support for Multi-file Checking

For cloud systems in which data blocks are subject to frequent modifications by group users, the TPA may need to check data integrity often to assure data integrity. In large-scale systems, performing integrity checking file by file is inefficient in terms of both bandwidth consumption and computational cost. Specifically, given a set of T different files $F_t = \{m_{ti,j}\}$ $1 \le t \le T, 1 \le i \le n_t, 0 \le j \le s_t - 1$, it is desirable if the TPA can aggregate integrity checking operations of T files into one challenge and one verification to reduce cost, where n_t is the number of data blocks in file F_t and s_t is the number of elements in each block. To this end, we design a batch verification algorithm based on our single file checking scenario, and enable the TPA to handle integrity checking of T files at the cost comparable to the single file scenario. In the batch verification algorithm, $KeyGen$, $Setup$ and $Update$ algorithms are same as those in the single file scenario respectively. Here we focus on introducing the $Batch - Challenge$, $Batch - Prove$ and $Batch - Verify$ algorithms.

Batch-Challenge: The challenge algorithm for checking T files is same as the single file scenario. Notably, the challenging message $CM = \{D, X, g^R, \mu\}$ now contains the information for data blocks of all these T files.

Batch-Prove: On receiving the challenging message $CM = \{D, X, g^R, \mu\}$, the cloud first runs the $Prove$ algorithm for each single file and generates $\psi_t, \pi_t, 1 \le t \le T$. Then, the cloud aggregates the proof information into two elements as

$$\pi = \prod_{t=1}^{T} \pi_t, \quad \psi = \prod_{t=1}^{T} \psi_t$$

The cloud also computes

$$y = f_{\vec{A}}(\mu) \ mod \ q$$

$$\vec{A} = \{0, 0, \sum_{t=1}^{T} \sum_{i \in D} p_i * m_{ti,0}, \cdots, \sum_{t=1}^{T} \sum_{i \in D} p_i * m_{ti,s_t - 1}\}$$

Finally, the cloud responds the TPA with proof information $Prf = \{\pi, \psi, y\}$.

Batch-Verify: On receiving the proof information Prf, the TPA first computes $\omega_t = \sum_{i \in D} B_{ti}$ for each file and generates $\eta = u^{\sum_{t=1}^{T} \omega_t}$. Then it verifies the integrity of these T files as

$$e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \stackrel{?}{=} \pi \cdot e(\kappa_0^{-y}, g^R) \tag{13}$$

If Eq.13 holds, the TPA outputs the verification result $VerifyRst$ as $Accept$ for these T files; otherwise, outputs $VerifyRst$ as $Reject$.

Based on above batch verification construction, we can see that the computational cost on TPA side for verification of T files is almost the same as that of one file.

Batch-Correctness: We analyze the correctness of our batch verification based on Eq.13 as follows:

$$
\begin{aligned}
& e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) \qquad (14)\\
&= e(u^{\sum_{i\in D,t=1}^{T} B_{ti}}, g)^{R\epsilon_0} \cdot e(g^{f_{\vec{A}}(\alpha)-f_{\vec{A}}(\mu)}, g)^{R\epsilon_0}\\
&= \prod_{i\in D,t=1}^{T} e(u^{B_{ti}}, g)^{R\epsilon_0} \cdot \prod_{i\in D,t=1}^{T} e(g^{f_{\beta_{ti}^{\vec{}}}(\alpha)}, g)^{R\epsilon_0}\\
&\cdot e(g^{-f_{\vec{A}}(\mu)}, g)^{R\epsilon_0}\\
&= \prod_{i\in D,t=1}^{T} e((u^{B_{ti}} \cdot g^{f_{\beta_{ti}^{\vec{}}}(\alpha)}), g)^{R\epsilon_0} \cdot e(g^{-f_{\vec{A}}(\mu)}, g)^{R\epsilon_0}\\
&= \pi \cdot e(\kappa_0^{-y}, g^R)
\end{aligned}
$$

Based on Eq.14, it is easy to validate the correctness of our batch verification construction.

D. Discussion

In this section, we discuss the error detection probability of our design and the choice of set D's size in the $Challenge$ algorithm. As mentioned in Section.III-B, instead of choosing all data blocks of a file to check its integrity, we randomly choose d blocks as set D, in order to save communication and computational costs while remaining an acceptable level of error detection probability. Specifically, as shown in ref. [6], if there are 1% corrupted data blocks, 460 challenging data will result in 99% detection probability, and 95% detection probability only requires 300 challenging blocks, no matter the total number (greater than 460 and 300 respectively) of data blocks in the file. Therefore, the number d can be considered a fixed number in our scheme once the required error detection probability is determined.

IV. Security Analysis

A. Assumption

Our security proof is based on the following hard problems:

Definition IV.1. ***Computational Diffie-Hellman (CDH) Problem*** *[16]*

Let a, b be two random numbers. Given (g, g^a, g^b), it is computationally intractable to compute the value of g^{ab}, where G is a cyclic group of order q and g is a generator of G.

Definition IV.2. ***Bilinear Diffie-Hellman (BDH) Problem****[17]*

Let G, G_1 be two groups of prime order q, $e : G \times G \to G_1$ be an admissible bilinear map and g is the generator of G. Given $\{g, g^a, g^b, g^c\}$ for some $a, b, c \in Z_q^*$, the probability $Pr[Adv(g, g^a, g^b, g^c) = e(g, g)^{abc}]$ is negligible for any probabilistic polynomial time adversary (Adv).

Definition IV.3. ***t-Strong Diffie-Hellman (t-SDH) Problem*** *[18]*

Let $\alpha \xleftarrow{R} Z_q^*$. Given input as a $(t+1)-tuple$ $(g, g^\alpha, \cdots, g^{\alpha^t}) \in G^{t+1}$, where g is the generator of a cyclic group G of order q. For any probabilistic polynomial time adversary (Adv), the probability $Pr[Adv(g, g^\alpha, \cdots, g^{\alpha^t}) = (c, g^{\frac{1}{\alpha+c}})]$ is negligible for any value of $a \in Z_q^*/-\alpha$.

B. Security Proof

We first prove the following theorem which will be needed for proving unforgeability of the proof information of our scheme.

Theorem IV.4. *If $g^{f_{\vec{A}}(\alpha)}$ can be forged by an existed probabilistic polynomial time adversary Adv, we can construct an algorithm B to efficiently compute the solution to t-SDH problem based on Adv.*

By following the idea in ref. [19], we prove Theorem.IV.4 as:

Proof: Suppose an Adv can generate $f_{\vec{A_1}}(\alpha)$ such that $g^{f_{\vec{A_1}}(\alpha)} = g^{f_{\vec{A}}(\alpha)}$, where $f_{\vec{A}}(x)$ and $f_{\vec{A_1}}(x)$ are known to the Adv. The Adv can construct another polynomial $f_{\vec{A_2}}(x) = f_{\vec{A}}(x) - f_{\vec{A_1}}(x)$. Therefore, $g^{f_{\vec{A_2}}(\alpha)} = g^{f_{\vec{A}}(\alpha)}/g^{f_{\vec{A_1}}(\alpha)} = g^{f_{\vec{A}}(\alpha)-f_{\vec{A_1}}(\alpha)} \in Z_q[x]$. As $f_{\vec{A_1}}(\alpha) = f_{\vec{A}}(\alpha)$ and $f_{\vec{A_2}}(\alpha) = 0$, α becomes a root of polynomial $f_{\vec{A_2}}(x)$. By factoring $f_{\vec{A_2}}(x)$ [20], B can easily find $SK = \alpha$. Based on $SK = \alpha$, B can easily find a number c and get $(c, g^{\frac{1}{\alpha+c}})$ as solution to the instance of the t-SDH problem given the system parameters. Note that, in our design, all information about α known to the adversary are in format $(g, g^\alpha, \cdots, g^{\alpha^t})$ or further blinded by elements independent to α, therefore in our scheme the $Adv's$ view is essentially the same as that in the t-SDH problem. ■

Theorem IV.5. *If there exists a probabilistic polynomial time adversary Adv that successfully convinces the TPA to accept the fake proof information for a corrupted file with non-negligible probability, we can use Adv to construct a polynomial time algorithm B that solves the BDH problem or the t-SDH problem with non-negligible probability.*

Proof: Suppose a probabilistic polynomial time adversary Adv can use fake proof information $Prf' = \{\psi', \pi', y\}, Prf' \neq Prf$ to bypass over the verification algorithm, where $Prf = \{\psi, \pi, y\}$ is the valid proof information. We use R, μ to denote random numbers used in the integrity $Challenge$ algorithm with valid proof information, $\vec{A}$ to denote the coefficient vector in the $Prove$ algorithm to generate valid proof information. As the valid proof information can pass the verification algorithm, we can get the following equation:

$$e(\eta, \kappa_0^R) \cdot e(\psi^R, \nu \cdot \kappa_0^{-\mu}) = \pi \cdot e(\kappa_0^{-y}, g^R) \qquad (15)$$

We now construct a simulator that uses the Adv to solve the BDH problem or the t-SDH problem. The simulator is given g^R,u^R,$g^{f_{\vec{A}(\alpha)}}$, PK and Prf, where Prf is the valid proof information for an integrity checking with D data blocks. To solve the instance of BDH problem, the simulator needs to output $e(g, g)^{\epsilon_0 R f_{\vec{A}(\alpha)}}$ with g^R, $g^{f_{\vec{A}}(\alpha)}$ and g^{ϵ_0}, where $f_{\vec{A}}(\alpha)$, R and ϵ_0 are not known. To solve the instance of $t-SDH$ problem, the simulator needs to output $(c, g^{\frac{1}{\alpha+c}})$ given $(g, g^\alpha, \cdots, g^{\alpha^t})$ in PK, where α is not known.

Assume the Adv can generate fake proof information Prf' and bypass over the verification algorithm with non-negligible probability, and submit Prf' to the simulator. Denote the random numbers chosen in the $Challenge$ algorithm as R', μ.

The simulator can get the following equation

$$e(\eta, \kappa_0^{R'}) \cdot e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu}) = \pi' \cdot e(\kappa_0^{-y'}, g^{R'}) \quad (16)$$

Based on Eq.15 with Eq.16, we can obtain:

$$\frac{e(\eta, \kappa_0^{R})}{e(\eta, \kappa_0^{R'})} \cdot \frac{e(\psi^{R}, \nu \cdot \kappa_0^{-\mu})}{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})} = \frac{\pi}{\pi'} \cdot \frac{e(\kappa_0^{-y}, g^{R})}{e(\kappa_0^{-y'}, g^{R'})} \quad (17)$$

Recall that, since $Prf' \neq Prf$, Prf' and Prf are different by at least one element, i.e., $\psi' \neq \psi$ or $\pi' \neq \pi$ or $y' \neq y$. The simulator first checks whether $\pi \stackrel{?}{=} \pi'$. If the $\pi \neq \pi'$, the simulator can rewrite Eq.17 as

$$e(g,g)^{R\epsilon_0 f_{\vec{A}(\alpha)}} = \frac{\pi}{\pi'} \cdot \frac{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})}{e(\kappa_0^{-y'}, g^{R'})} \cdot \frac{e(\eta, \kappa_0^{R'})}{e(\eta, \kappa_0^{R})} \quad (18)$$

Since, R', π, π', μ, y' are known to the simulator, it can compute $\frac{\pi}{\pi'} \cdot \frac{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})}{e(\kappa_0^{-y'}, g^{R'})}$ and $e(\eta, \kappa_0^{R'})$ with the PK. In addition, as u^R is known to the simulator, he can also compute $e(\eta, \kappa_0^{R})$ similar to $e(\eta, \kappa_0^{R'})$ by replacing u with u^R and $\kappa_0^{R'}$ with κ_0. In this case, the simulator solves the instance of the BDH problem by outputting $e(g,g)^{R\epsilon_0 f_{\vec{A}(\alpha)}} = \frac{\pi}{\pi'} \cdot \frac{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})}{e(\kappa_0^{-y'}, g^{R'})} \cdot \frac{e(\eta, \kappa_0^{R'})}{e(\eta, \kappa_0^{R})}$, where $f_{\vec{A}}(\alpha)$, R and ϵ_0 are not known to it. Therefore, $\pi = \pi'$

If $\pi = \pi'$, the simulator checks whether $y \stackrel{?}{=} y'$. If the $y \neq y'$, he can replace R with R' in Eq.15 and get

$$e(\eta, \kappa_0^{R'}) \cdot e(\psi^{R'}, \nu \cdot \kappa_0^{-\mu}) = e(g,g)^{R'\epsilon_0} \cdot e(\kappa_0^{-y}, g^{R'}) \quad (19)$$

where, $e(g,g)^{R'\epsilon_0} = \pi$. Since $\pi = \pi'$, the simulator can rewrite the Eq.17 based on Eq.19 as

$$\frac{e(\psi^{R'}, \nu \cdot \kappa_0^{-\mu})}{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})} = \frac{e(\kappa_0^{-y}, g^{R'})}{e(\kappa_0^{-y'}, g^{R'})} \quad (20)$$

The simulator can denote ψ as g^{θ} and ψ' as $g^{\theta'}$ and output

$$\left(\frac{e(\psi, \kappa_0)}{e(\psi', \kappa_0)}\right)^{(\alpha-\mu)R'} = \frac{e(g, \kappa_0)^{-yR'}}{e(g, \kappa_0)^{-y'R'}} \quad (21)$$
$$\theta(\alpha - \mu) + y = \theta'(\alpha - \mu) + y'$$
$$\frac{(\theta - \theta')}{y' - y} = \frac{1}{\alpha - \mu}$$

Then, the simulator can compute

$$\left(\frac{\psi}{\psi'}\right)^{\frac{1}{y'-y}} = g^{\frac{\theta-\theta'}{y'-y}} = g^{\frac{1}{\alpha-\mu}} \quad (22)$$

and output $(-\mu, g^{\frac{1}{\alpha-\mu}})$ as a solution of the t-SDH problem. Therefore, $y' = y$.

If $\pi = \pi'$ and $y = y'$, the simulator checks whether $\psi \stackrel{?}{=} \psi'$. If $\psi \neq \psi$, the rewrite Eq.20 as

$$\frac{e(\psi^{R'}, \nu \cdot \kappa_0^{-\mu})}{e(\psi'^{R'}, \nu \cdot \kappa_0^{-\mu})} = 1 \quad (23)$$

As $\psi' \neq \psi$, the simulator can infer $\alpha = \mu$ based on Eq.23. In this case, the simulator can also output $(\mu, g^{\frac{1}{\alpha+\mu}})$ as a solution of the t-SDH problem. Therefore, $\psi' = \psi$. In addition, as proved in Theorem IV.4, $\psi = g^{f_{\vec{A}}(\alpha)}$ cannot be forged, outputting $\psi' = \psi$ needs the knowledge of actual data blocks.

Theorem.IV.5 is proved. ■

Security against collusion attacks of our scheme can be proven as follows:

Theorem IV.6. *If there exists a probabilistic polynomial time adversary Adv that can collude with the cloud and revoked users to generate authentication tags on behalf of valid users, we can construct a polynomial time algorithm B that solves the CDH problem.*

Proof: Suppose the a probabilistic polynomial time adversary Adv can generate the block tags impersonating a valid user u_k. Therefore, he will be able to compute $u^{B_i\epsilon_k} \cdot g^{\epsilon_k f_{\vec{\beta_i}}(\alpha)}$ as part of the authentication tags. Assuming $u = g^t$ for an unknown integer t, we have $u^{B_i\epsilon_k} \cdot g^{\epsilon_k f_{\vec{\beta_i}}(\alpha)} = g^{U \cdot \epsilon_k}$, where $U = tB_i + f_{\vec{\beta_i}}(\alpha)$. Note that, $g^U = u^{B_i} \cdot g^{f_{\vec{\beta_i}}(\alpha)}$ can be computed by the Adv if he knows the data block and $\kappa_k = g^{\epsilon_k}$ is public key; U and ϵ_k are integers in Z_q^* unknown to the Adv. In this case the Adv actually has solved CDH problem. ■

V. Performance Evaluation

A. Numerical Analysis

In this section, we numerically analyze our proposed scheme and compare it with ref. [13] in terms of computational cost and communication cost. For simplicity, in the rest of this paper, we use EXP and MUL[1] to denote the complexity of one exponentiation operation and one multiplication operation on Group G respectively.

1) Computational Cost: As shown in Section.III, there are 7 algorithms in our scheme: $KeyGen$, $Setup$, $Challenge$, $Update$, $Prove$, $Verify$ and $User\ Revocation$. $KeyGen$ and $Setup$ are pre-processing procedures, which can be performed by group users off-line and will not influence the real-time verification performance. In the $KeyGen$ algorithm, the master user needs to perform $(s + K + 4)$ EXP operations to generate public keys and master keys for the system, where s is the number of elements in block and K is the number of group users. To setup the system, the master user conducts $(s + 2)n$ EXP and sn MUL operations for each file, where n is the number of blocks in a file. When a user needs to modify or add data blocks, he executes the $Update$ algorithm with $(s + 2)$EXP+$(s + 1)$MUL operations to generate the corresponding tags. In order to check the integrity of a file, the TPA first performs the $Challenge$ algorithm to generate the challenging message CM by choosing a constant number of random numbers at a negligible cost. The cloud server then runs the $Prove$ algorithm with s EXP, $(s + d)$ MUL and d Pairing operations, where d is a constant number of blocks selected for challenging as discussed in Section. III-D. To verify the integrity of the file, the TPA only needs 6 EXP, 3 MUL and 3 Pairing operations. This property is interesting because such a cost can even be affordable to less powerful devices such as mobile phones. If there are some blocks last modified by revoked users, the TPA only needs to perform

[1] When the operation is on the elliptic curve, EXP means scalar multiplication operation and MUL means one point addition operation.

	Single Task		Multiple Tasks		User Revocation
	Comp.Cost (User)	Comm.Cost	Comp.Cost (User)	Comm.Cost	Comp.Cost (Cloud)
Ref.[13]	$(d+C)$EXP +$(d+2C)$MUL +$(C+1)$Pairing	$d*\|index\|+2C\|G\|$	$(d+C)T$ EXP +$(d+2C)$T MUL +$(C+1)$T Pairing	$dT*\|index\|+2CT\|G\|$	Y Exp
Our Scheme	6 EXP + 3 MUL + 3 Pairing	$d*\|index\|+(C+3)\|G\|$ $+2\lambda$	6 EXP + 3 MUL + 3 Pairing	$d*\|index\|+(C+3)\|G\|$ $+2\lambda$	Y EXP+Y Pairing

Table.1 Complexity Summary: in this table, C is number of users that modify files, d is the number of of blocks selected for challenging, $|index|$ is the size of block index, $|G|$ is the size of a group element, λ is the size of security parameter and T is the number of files for verification; EXP and MUL are one multiplication operation and one exponentiation operation on Group G respectively, Pairing is a bilinear pairing operation.

one more EXP and one more MUL operations compared to the scenarios without user revocation. In case multiple files shall be verified at the same time, our design can batch the verification operations of these files and aggregate them into one operation. Consequentially, the TPA only needs 6 EXP, 3 MUL and 3 Pairing operations to perform multiple file checking, the cost of which is the same as the single file scenario. To revoke a group user, no computational cost is required for group users; the cloud server needs Y pairing and Y EXP operations to update the corresponding tags, where Y is the number of data blocks last modified by the revoked user.

We now compare our proposed scheme with the existing scheme [13] and summarize the result in Table.1. To verify the integrity of a single file, ref. [13] costs the TPA $(d+C)$EXP+$(d+2C)$MUL+$(C+1)$Pairing operations, where C is number of users who modify this file. Our design can migrate most computational cost to cloud servers and makes the cost of the TPA independent to the number of challenging blocks and group users. In order to process multiple verification tasks simultaneously, the cost of the TPA in ref. [13] is linear to the number of tasks. In contrast, our scheme can aggregate operations brought by multiple tasks and make the cost similar to the single file scenario, and thus outperforms ref. [13].

2) Communication Cost: In our scheme, the communication cost for data integrity checking mainly comes from the challenging message CM and the proof information Prf. The size of the $CM = \{D, X, g^R, \mu\}$ is $d*|index|+(C+1)|G|+\lambda$ bits, where $|index|$ is the size of block index and $|G|$ is the size of a group element. For the proof information $Prf = \{\pi, \psi, y\}$, there are two group elements and the result of a polynomial with $2|G|+\lambda$ bits. If there are some blocks last modified by revoked users, $Prf = \{\pi, \vartheta, \psi, \chi, y\}$ and the size is $4|G|+\lambda$ bits. Therefore, the total communication cost of an integrity verification task is $d*|index|+(C+3)|G|+2\lambda$ bits ($d*|index|+(C+5)|G|+2\lambda$ bits if there are user revocations). Considering the simultaneous checking of multiple files, our batch verification design allows users to aggregate these tasks into one challenge and one proof, and thus achieving the same communication cost as the single file scenario. When a user revocation occurs, our schemes only requires the master user to notify this revocation to cloud server, the TPA and other users, which introduces negligible communication cost.

Now, we compare our proposed scheme with the existing scheme [13] and summerize the result in Table.1. In ref.[13] the communication cost for single verification task is $d*|index|+2C|G|$ bits which is attributed to the challenge and proof generation processes and is comparable to our scheme. However, when processing multiple tasks together, the size of proof information in ref. [13] will increase linearly to the number of tasks as shown in Table.1, where T is the number of files for verification. Differently, our batch verification design omits this kind of linear growth with information aggregation. In order to revoke a user, although ref. [13] has a similar cost to our scheme, their user revocation solution assumes non-collusion occurs between cloud servers and users.

B. Experimental Results

To evaluate the performance of our proposed scheme, we fully implemented our proposed scheme on Aamazon EC2 cloud using JAVA with JAVA Pairing-Based Cryptography Library (jPBC) [21]. On the cloud server, we deploy nodes running Linux with 8-core CPU and 32GB memory. The TPA is a desktop running Linux with 3.4GHz Intel i7-3770 CPU and 16GB memory. Machines for group users are laptops running Linux with 2.50GHz Intel i5-2520M CPU and 8GB memory. We set the security parameter $\lambda = 160$ bits, which achieve 1024-bits RSA equivalent security since our implementation is based on ECC. The shared files used for testing are open source codes Apache OpenOffice [22] which has 66,359 files. We set size of each data block as $4KB$, which is consistent with the ref.[6], [12]. To measure the influence of group size, we conduct experiments from small group with 5 users to large group with 150 users. In our experiments, we mainly evaluate the computational and communication performance of our scheme. All experimental results represent the mean of 50 trials. Our implementation is not optimized (e.g. it is a single process/thread program in some parts). Therefore, further performance improvements of our scheme is possible.

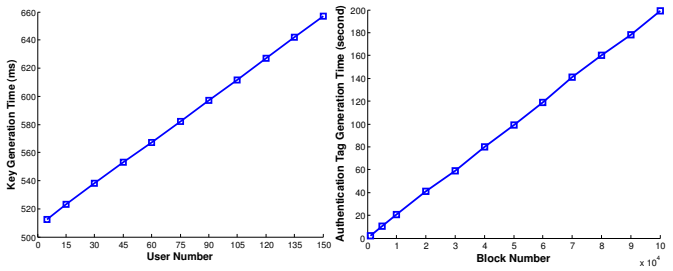

Fig. 2. (a) Key Generation Time (b) Authentication Tag Generation Time

1) System Setup: We first evaluate the generation of public keys, master keys and secret keys for the system. Our result in Fig.2(a) indicates that the key generation cost is proportional to the group size, which is consist with our analysis in Section.V-A1. To show the performance of authentication tag generation, we vary the number of blocks in the file is from 1000 to 100,000. As shown in Fig.2(b), the tag generation time increases proportionally to the number of blocks, from 2.11s to 198.23s. Note that, the system setup cost is one-time, which can be conducted off-line and will not influence the realtime performance of integrity checking.

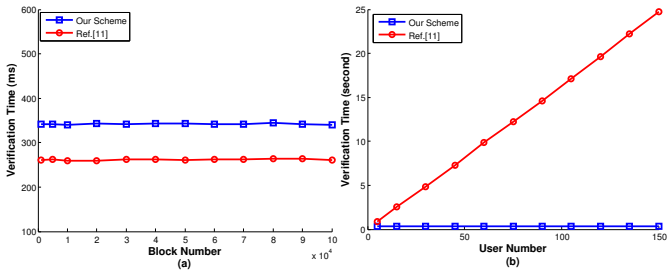

Fig. 3. (a) Verification Time On Different File Size (b) Verification Time On Different User Number

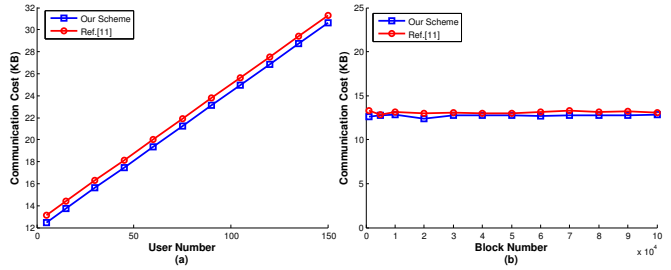

Fig. 4. (a) Communication Cost On Different User Number (b) Communication Cost On Different File Size

2) Real-time Checking - Single File: As we discussed in Section.III-D, we can set the number of challenging block as 460 in our experiments to achieve 99% detection probability. We first measure the performance of the checking of single file. Fig.3(a) and Fig.3(b) show that the verification performance on the TPA side is constant, i.e., the user number and file size have no influence on the TPA computational cost, which is consistent with our previous analysis in Section.V-A1. Although we do not conduct experiments on larger groups and files, it is easy to validate that the computational cost on the TPA side is constant regardless of the number of group users. However, as shown in Fig.3(b), the computation cost of the TPA in ref. [13] is proportional to the number of user and is thus much more expensive than our scheme as group size increases. Considering the communication cost, when we change the number of users that modify blocks in the file from 5 to 150, Fig.4(a) shows that our scheme allow a TPA to verify the integrity of a file at the communication cost from 12.78KB to 30.87KB. Fig.4(b) indicates that file size does not have influence on the communication cost of our scheme. Note that, the communication cost in our design is only 30.87KB even 150 users modify the blocks of the file at the same time, which can be efficiently handled in today's networks. Compared with ref. [13], we achieved comparable communication cost as shown in Fig.4(a) and Fig.4(b).

3) Multiple Files Checking: To show the benefits of our batch verification design for multiple files scenario, we change number of simultaneous verification tasks from 250 to 2000. Since the group size does not influence the checking performance of the TPA, we set group size as 50 here. As shown in Fig.5(a), the computational cost of the TPA side is around 400ms with the increasing of simultaneous task number. In addition, Fig.5(b) shows that the communication cost of our scheme does not change with the number of

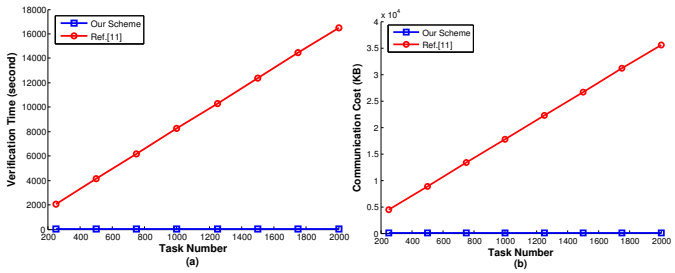

Fig. 5. (a) Verification Time On Different Task Number (b) Communication Cost On Different Task Number

tasks/files. In contrast, Fig.5(a) and Fig.5(b) indicate that in ref. [13] both computational cost and communication cost are linear to the number of simultaneous integrity checking tasks, which significantly limit its scalability in terms of the number of tasks.

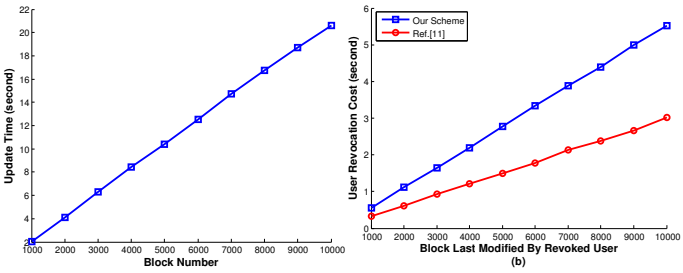

Fig. 6. (a) Block Update Cost (b) User Revocation Cost

4) Update and User Revocation: The update procedure of data blocks in our scheme is similar to the setup procedure. As shown in Fig.6(a), the update cost is proportional to the number of blocks for modification. To revoke a user, no computational cost and communication cost are required for group users and the TPA in our scheme. The cloud server can help the group users to temperately update the corresponding authentication tags when a user revocation occurs. Fig.6(b) shows that our tag update performance is comparable with ref. [13]. However, it is worth to note that the user revocation efficiency in ref. [13] is based on the non-collusion assumption, which does not exist any longer in our design.

From the above experimental results, it is clear that the file size only influences the pre-processing procedures of our proposed scheme, which is one-time cost and does not have any effect on real-time performance of integrity checking. While most existing work such as ref. [13] is limited by the group size and task number due to the performance, our scheme can efficiently handle large size of groups and/or a large number of tasks. Therefore, our proposed scheme has high scalability in terms of the sizes of files/groups as well as the number of tasks.

VI. Applications

One potential application is cloud-based open source software development, wherein source code and corresponding documents are stored on public storage platform such as cloud servers. In open source software, the number of contributors can be very large, and the member join and leave is very

frequent. In this case, each contributor should be able to modify codes with integrity checking, and the performance should not be affected by the number of contributors. In addition, the join and leave of contributors should be handled efficiently without affecting other contributors and the integrity checking performance. Our proposed solution is suitable for this kind of application because its real-time performance is not affected by group size as shown in above analysis. At the same time, the revocation of a contributor can be delegated to cloud servers without help of any other contributors.

Another possible application scenario is cloud-based collaboration of organizational IT department, which may have a relatively small number of group users. But the documents (e.g., software code, system bug report, daily work reports, operational data) of an organizational IT department may be subject to frequently modification by different employees due to the daily operational needs. This kind of high-frequency modification requires fast integrity checking for each modification and efficient processing for a large number of files. As shown in our analysis and experimental results, our scheme can aggregate the integrity checking of multiple documents that underwent modifications by multiple employees. Therefore, our scheme is appropriate for this kind of application.

VII. Conclusion

In this paper, we propose a novel data integrity checking scheme that supports multiple writers to share data. Our proposed scheme is featured by salient properties of public integrity checking and constant computational cost on the user side. We achieve this through our innovative design on polynomial-based authentication tags which allows aggregation of tags of different data blocks. For system scalability, we further empower the cloud with the ability to aggregate authentication tags from multiple writers into one when sending the integrity proof information to the verifier (who may be general cloud users). As a result, just a constant size of integrity proof information needs to be transmitted to the verifier no matter how many data blocks are being checked and how many writers are associated with the data blocks. Moreover, our novel design allows secure delegation of user revocation operations to the cloud even if cloud servers collude with malicious users. Last but not least, our proposed scheme allows aggregation of integrity checking operations for multiple tasks (files) through our batch integrity checking technique. As compared to existing schemes, our solution has obvious advantages in terms of efficiency, scalability and security. Extensive numerical analysis and real-world experiments validate the performance of our scheme. Rigorous security analysis shows that our solution is provably secure.

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