

Solving the Secure Storage Dilemma: An Efficient Scheme for Secure Deduplication with Privacy-Preserving Public Auditing

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Abstract. Existing cloud storage systems receive the data in its plain form and perform conventional (server-side) deduplication mechanisms. However, disclosing the data to the cloud can potentially threaten the security and privacy of users, which is of utmost importance for a real-world cloud storage. This can be solved by secure deduplication mechanisms which enables the user to encrypt the data on the client-side (or via an encryption-as-a-service module) before uploading it to the cloud storage. Conventional client-side encryption solutions unfortunately make the deduplication more challenging because of the offline dictionary attacks by which the key is derived from the data. Additionally, encryptions become computationally indistinguishable when each owner possess different encryption keys. Hence, trivial encryption solutions may either lead to high storage or bandwidth costs on both the client and the server sides. Privacy-preserving public auditing schemes, on the other hand, is also crucial because the clients outsource their data to the cloud providers and then permanently deletes the data from their local storages. In this paper, we consider the problem of secure deduplication over encrypted data stored in the cloud while supporting a privacy-preserving public auditing mechanism. We show that existing solutions cannot support both goals simultaneously due to the conflict of their security and efficiency requirements. In this respect, we present an efficient and secure deduplication scheme that supports client-side encryption and privacy-preserving public auditing. We finally show that our scheme provides better security and efficiency with respect to the very recently proposed existing schemes.

Keywords: Secure Client-Side Deduplication, Public auditing, Privacy, Cloud Storage.

1 Introduction

When n clients upload the same copy of a file F , the cloud provider stores only one copy that is sent back to these clients upon download. This is called *deduplication* technology which is a useful method for reducing

data redundancy on storage space, reducing computations on disk storage, saving on network bandwidth, and speeding up the actual backups. The goal of a deduplication mechanism is to find out basically all identical files on the storage space. More storage costs on the server-side would lead to the clients to pay higher storage fees making deduplication to be one of the most cost saving mechanism for Cloud Storage Providers (CSPs).

In terms of location of deduplication processing, the underlying techniques can be classified into two methods: (1) deduplication occurs before the upload on the client-side (see Figure 1), (2) deduplication occurs after the upload on the server-side (see Figure 2). Deduplication can also be classified into two methods in terms of data processing method: (1) deduplication at a block level where the data is divided into smaller fixed-size or variable-size blocks and only a single copy of each block is stored [1], (2) at a file level where only a single copy of a file is stored [2].

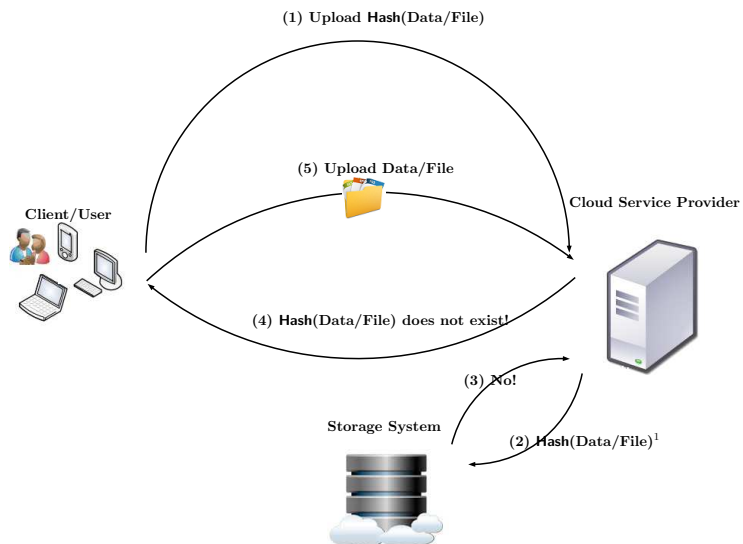


Fig. 1. Client-Side Deduplication. Note that if the answer is Yes! at Step (3) then a proof of ownership protocol is required to be executed between the user and the server.

The server-side deduplication allows a server to check whether the two stored files are identical. In this case, the client first uploads a file, and then the server can internally check if there is a duplication. In this case, the clients do not know whether there is a duplicate. Server-side deduplication mechanisms are easy to handle and already in use [3–5].

However, server-side solutions only reduce the cost of storage for the server and do not reduce the bandwidth.

Client-side deduplication is more interesting because both the clients and the CSPs do not want the files to be uploaded if they already exist in the server which also save high bandwidth costs [6,7]. However, the client-side deduplication requires a client to prove the possession of the data without sending the actual data (e.g., the hash of the data instead of full plaintext where hash is a function taking a string as input and generates a unique compressed string). Namely, duplication control is performed on the client-side before the users upload their files. More concretely, the client-side deduplication is jointly performed by the client and the server to check the existence of the uploading files in the server. In general, proof of ownership mechanisms are used to assure that the owner has the file without uploading it to the server. For example, a malicious user which does not own a file F may obtain its hash value, and then may send to the cloud server to prove that the file was actually on the local storage. Therefore, there must be a secure cryptographic protocol for the proof of possession mechanism.

User data is already known to the CSPs in the existing deduplication solutions. What if the user does not want to reveal her data to the cloud providers while the CSPs still desire deduplication? The solution of this problem is known as *secure deduplication* and is not easy for the following reason: Assume that Alice and Bob have the same file F , and they encrypt F using a conventional cryptographic scheme like AES under their own secret symmetric keys K_A and K_B , respectively. Finally, they upload the ciphertexts $F_A = \text{Enc}_{K_A}(F)$ and $F_B = \text{Enc}_{K_B}(F)$ to the CSP, respectively. However, it is now computationally hard for the CSP to decide whether F_A and F_B are the same (because of the underlying encryption algorithm and $K_A \neq K_B$). Furthermore, even if the CSP could decide, it would be difficult for the CSP to store F_A and F_B in a short copy that allows both Alice and Bob to obtain the plaintext F by decrypting it. Therefore, it should be ensured that the resulting ciphertexts are the same without giving any sensitive information about F to the CSPs. In the case that semantically secure encryption is used, secure deduplication will also be impossible because neither Alice nor Bob can decide whether the two ciphertexts correspond to the same plaintext. Note also that offline dictionary attacks are applicable if the keys are derived from the F (i.e., $K_A (= K_B) = H(F)$ where H is a conventional hash function mapping inputs of arbitrary length to an output of a fixed length). Existing solutions in use unfortunately have either security and privacy issues

(e.g., Dropbox, Amazon AWS, Google Drive, Bitcasa, Mozy, Memopal apply client-side deduplication [6, 8].).

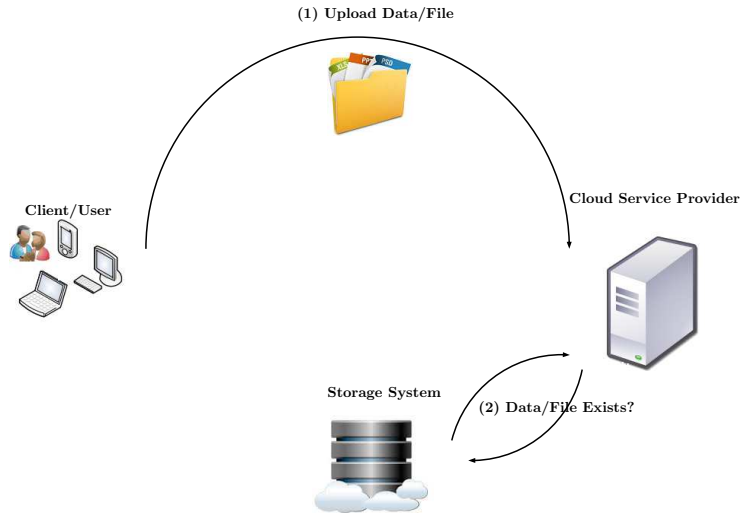


Fig. 2. Server-Side Deduplication

As a growing need, data integrity means that data should be correctly stored in the cloud server, and any modification without the consent of a user (e.g., if data is lost, becomes corrupt, modified or compromised) should easily be detected. More concretely, users store files to the cloud and want to guarantee that they are never changed or removed [9].

Integrity auditing is usually solved by using either message authentication codes (MACs) or digital signatures. Complete assurance of data integrity in an efficient manner is also not easy to handle. The main reason of scalability problem is that the computing resources is not run locally and the users cannot be sure that the CSP is correctly performing the computation. A direct solution may be first is to download complete files and check the integrity. However, this requires very high communication cost which resulting a non-scalable solution. Hence, to reduce the communication cost the work is generally delegated to a Third Party Auditor (TPA). Briefly, the TPA is assumed to be semi-honest and continuously performs the integrity auditing on behalf of the users by querying only a random subset of the small pieces of data [10–16]. The TPA does not need the client through the auditing process to assure that her/his data stored is indeed in the CSP.

1.1 Contributions

Privacy-preserving public auditing and secure deduplication are the two main lines of the research for secure storage of the outsourced data. However, these solutions may contradict each other because existing privacy-preserving auditing mechanisms require both the data and its signatures while deduplication requires not to upload the duplicated data again. The difficulty in solving this contradictory problem comes from the fact that once a user signs and uploads a file then how it can be possible for the next user to audit the same duplicated file without sending the actual file and her signatures. In this paper, we focus on this contradictory problem and propose an efficient solution for secure deduplication with a privacy-preserving public auditing mechanism.

Our solution supports client-side encryption while also assuring proof of ownership. In order to provide secure deduplication and privacy-public auditing simultaneously, we basically propose to utilize anonymous public-key certificate architectures [17–21]. Hence, a user can easily and anonymously audit a file and verify the signatures without compromising the privacy of the users. Furthermore, the CSP cannot obtain any information about the data and the TPA assures that the data is available and has not been changed.

To the best of our knowledge, the only existing schemes supporting both secure deduplication and public auditing are belong to [22] and [23]. Firstly, the authors in [22] utilize an honest *mediator* which obtains the data in plaintext form and performs a block-level deduplication before they are sent to the cloud. However, since the mediator requires to be in the client’s company environment not many deduplication would occur on a small size of enterprises, and hence, this solution loses the benefits of deduplication. Secondly, the authors in [23] utilizes an honest a TPA which also receives the data itself from the user. However, this scheme has also several security and efficiency drawbacks. On the one hand, their scheme is too inefficient because of the use of the Type-1 pairing in their setting. More concretely, for a secure implementation they need supersingular elliptic curves over large prime fields which significantly increase the complexity of their protocol (see [24] for details). On the other hand, uploading the file to an honest TPA a strong assumption because TPAs are always assumed to be semi-honest in all privacy-preserving existing auditing mechanisms to prevent privacy violations. Also, and more importantly, because the data is also sent to the TPA the bandwidth advantage of the client-side solutions is completely eliminated for the user. Their

protocol is also too inefficient because of the same reasoning as above (i.e., they use Type-1 pairing [24]).

To that extent, our proposal is the first scheme for secure storage providing both a secure deduplication mechanism and a privacy-preserving public auditing solution simultaneously. In particular, it maintains the storage and bandwidth savings of the client-side solution. Furthermore, it can also support both file and block level deduplication.

1.2 Roadmap

In Section 2, we summarize the related works by focusing on deduplication, privacy-preserving public auditing, and secure deduplication with privacy-preserving public auditing separately. We then give the necessary background and preliminaries in Section 3 that will be used throughout the manuscript. In Section 4, we propose our security model, and Section 5 presents our mechanism for secure deduplication with privacy-preserving public auditing. We analyze the security of our protocol in Section 6 and give its complexity in Section 7. Finally, Section 8 concludes the paper.

2 Related Work

2.1 Secure Deduplication

The concept of secure deduplication is interesting for both research and industrial community because of reducing high costs in cloud computing environment (e.g., Amazon S3, Dropbox, OwnCloud, TeamDrive, Box, OneDrive (formerly SkyDrive), Google Drive, DepSky, and SugarSync). The first solution is to apply *convergent encryption* mechanism which is designed by Douceur et al. [25]. The data here is encrypted using a symmetric encryption scheme with a key which is deterministically derived from the hash of the data content. The convergent encryption mechanism is actively used by commercial CSPs like Amazon S3, Dropbox, Google, and Bitcasa [26, 27]. Note that convergent encryption does not provide semantic security because of content-guessing attacks using the deterministic nature of the content hashing ².

Several secure deduplication schemes have already been proposed [6, 28–30]. In [31], Harnik et al. showed some attacks in the case of client-side deduplication which can lead to data leakage. Later, the concept

² Semantic security in this context means that ciphertexts leak no information about the underlying plaintexts except the knowledge of their equalities.

of proof of ownership has been introduced to prevent such attacks [32, 33]. However, none of these results guarantee the confidentiality against semi-honest or malicious CSPs. In [34], the authors discuss performance, back-up, and security and privacy issues of Mozy, Carbonite, Dropbox, and CrashPlan. [35] the authors specifically analyze the Dropbox client software with its communication protocol, and show the security and privacy issues within the Dropbox such as unauthorized access to the stored files.

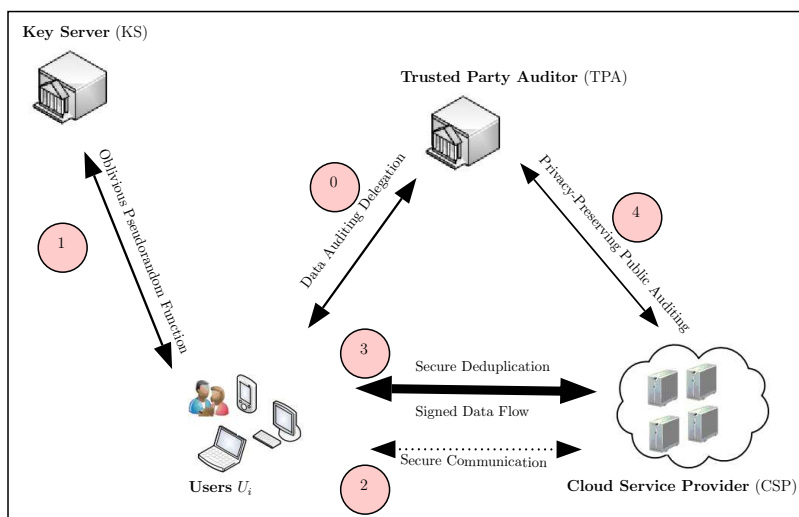


Fig. 3. A Privacy-Preserving Public Auditing Model with Secure Deduplication: (0) i -th user U_i is delegating the auditing mechanism to a TPA, (1) a protocol for oblivious pseudorandom random function is run between the i -th user U_i and the KS, (2) the i -th user U_i securely communicates with the CSP, (3) the i -th user U_i uploads a file to the CSP which supports both the secure deduplication and the privacy-preserving public auditing properties, (4) a privacy-preserving public auditing is run between the TPA and the CSP.

Later, Bellare, Keelveedhi, and Ristenpart in [26] formalized the convergent encryption, which is defined as *message-locked encryption*. Message-locked encryption basically allows a user to encrypt the data under a symmetric key sk where $sk = H(M)$, H is a conventional hash function [26, 30, 36–40]. Therefore, a plaintext M will lead to the same cipher-

text $\text{Enc}_{sk}(M)$. Furthermore, only sk is stored and her encrypted file M in the CSP in order to retrieve later and decrypt it. However, this mechanism of Bellare et al. does not provide semantic security and only satisfies security for unpredictable messages (since the secret key can be easily obtained for predictable files, and therefore, the knowledge of initialization vectors of the underlying symmetric encryption schemes become useless). Bellare et al. later presented another scheme called DupLESS which is a server-aided encryption mechanism for deduplicated storage and ensures semantic security [26].

In [41], the authors propose the first secure cross-user deduplication scheme that provides the client-side encryption. The scheme is based on using a PAKE (Password Authenticated Key Exchange) protocol and does not require any additional independent servers. Furthermore, in [42], the authors present a specific secure architecture enabling the encrypted cloud media center.

2.2 Privacy-preserving public auditing

There are basically two research direction of data integrity in the cloud setting: Provable Data Possession (PDP) and Proof of Retrievability (POR). PDP was first introduced by Ateniese et al. [43, 44] for assuring that the CSPs indeed possess the files without retrieving or downloading the whole data. It is basically a challenge-response protocol which assures a client that her data stored on the cloud has not been modified without being detected. The protocol is realized by asking a random proper subset of blocks from the CSPs to prove that they indeed possess these blocks. The verifier TPA, which is assumed to be semi-honest, only checks a small portion of data. In [45], Wang et al. proposed proxy PDP in public clouds. It is also rather important to utilize stateless and semi-honest third party verifiers (i.e., auditors) [46–51]. In general, existing mechanisms comprised of four main procedures: (1) signature generation by the client, (2) challenges by the TPA, (3) proof by the CSP, and (4) verification by the TPA.

Compared to PDP, POR (which is a challenge-response protocol) not only assures the cloud servers possess the target files, but also guarantees their full recovery [52–54].

2.3 The secure storage dilemma: Secure deduplication with privacy-preserving public auditing

Secure management and verification of integrity for the outsourced data contents are of importance in practice. Although they have been stud-

ied extensively in industrial and academic field a trivial combination of privacy-preserving public auditing and secure deduplication mechanisms does not simply solve both the secure deduplication and integrity auditing in an efficient manner (see Figure 3). This is because achieving storage efficiency contradicts with the deduplication of authentication tags (i.e., signatures). If the deduplicated data and its authentication tags were never sent to the cloud then how could the user audit data integrity on the cloud side?

We would like to first highlight that there are many solutions that deal with public auditing with deduplication [55, 56]. However, these solutions do not provide secure deduplication simultaneously because files are already visible to storage providers. In this respect, to the best of our knowledge, only the following papers consider both secure deduplication and public auditing notions simultaneously.

In [57], the authors claim that public auditing with deduplication. However, this scheme does not provide secure deduplication because the data is available in its plaintext form on the cloud-side.

In [22], the authors propose a variant of client-side deduplication mechanism where a *mediator* performs a block-level deduplication on users' data before they are sent to the cloud. Privacy-preserving public auditing is performed as usual via the trusted party auditor using Wang et al.'s scheme [48]. The main drawback of this scheme is to use of a mediator in the client's company environment. Therefore, not many deduplication would occur on a small size of enterprises instead of performing deduplication on the large scale CSPs.

Li et al. [23] proposed SecCloud+ which aims to solve both data integrity and deduplication by using the convergent encryption technique. The main drawback of this scheme is to upload the file to the TPA, which violates the privacy of the user. To the best our knowledge, disclosing the data to the TPA is never modeled under the existing privacy-preserving public auditing schemes. Furthermore, it does not eliminate the bandwidth advantage for a user. Their protocol is also too inefficient because of the use of the Type-1 pairing in their setting [24].

3 Preliminaries and Notation

Bilinear Maps for Auditing Schemes. Bilinear maps are one of the best candidate for enabling auditing property. We follow the lines of [58, Chapter IX], [24] for the properties of pairings.

Let $(\mathbb{G}_1, +)$ and $(\mathbb{G}_2, +)$ be two additive cyclic groups of order q with $\mathbb{G}_1 = \langle Q \rangle$ and $\mathbb{G}_2 = \langle P \rangle$, (\mathbb{G}_3, \cdot) be a multiplicative cyclic group of order q , where q is a prime number, 0 denotes the identity element of $\mathbb{G}_1, \mathbb{G}_2$, and 1 denotes the identity element of \mathbb{G}_3 . Assume that Discrete Logarithm Problem (DLP) is hard in both \mathbb{G}_1 and \mathbb{G}_2 (i.e., given a random $R \in \mathbb{G}_1$ (or $\in \mathbb{G}_2$), it is computationally infeasible to find an integer $x \in \mathbb{Z}$ such that $R = x \cdot Q$). A *bilinear map* is a map $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_3$ satisfying the following properties:

- **Bilinearity:** For all $P_1, Q_1 \in \mathbb{G}_1, P'_1, Q'_1 \in \mathbb{G}_2$, e is a group homomorphism in each component, i.e.
 1. $e(P_1 + Q_1, P'_1) = e(P_1, P'_1) \cdot e(Q_1, P'_1)$,
 2. $e(P_1, P'_1 + Q'_1) = e(P_1, P'_1) \cdot e(P_1, Q'_1)$.
- **Non-degeneracy:** e is non-degenerate in each component, i.e.
 1. For all $P \in \mathbb{G}_1, P \neq 0$, there is an element $Q \in \mathbb{G}_2$ such that $e(P, Q) \neq 1$,
 2. For all $Q \in \mathbb{G}_2, Q \neq 0$, there is an element $P \in \mathbb{G}_1$ such that $e(P, Q) \neq 1$.
- **Computability:** There exists an algorithm which computes the bilinear map e efficiently.

Furthermore, the *Computationally Diffie-Hellman* (CDH) problem in a multiplicative group \mathbb{G} with a generator g is defined as follows: given only $g, g^x, g^y \in \mathbb{G}$ where $x, y \in \mathbb{Z}$, compute g^{xy} without the knowledge of x or y [59]. We also assume that the CDH problem is computationally intractable (which will be used for the underlying privacy-preserving public auditing mechanism).

For the sake of easy notation, we use multiplicative notation for elements of $\mathbb{G}_1, \mathbb{G}_2$, and \mathbb{G}_3 in our protocol descriptions.

Symmetric Encryption & Hash Functions. We denote a symmetric key encryption with

$$\mathcal{E}_{\text{sym}} = \text{SymEnc}_k(M)$$

and decryption with

$$M = \text{SymDec}_k(\mathcal{E}_{\text{sym}}),$$

where k is a secret key and M is a plaintext to be encrypted. We denote $H_1(\cdot)$ for the conventional collision resistant hashing process where

$$H_1 : \{0, 1\}^* \rightarrow \{0, 1\}^\ell,$$

where ℓ is a fixed length of output (e.g., if H_1 is SHA-512 based, then $\ell = 512$). Denote $H_2(\cdot)$ for a secure hashing of an arbitrary binary string to a point on the elliptic curve group \mathbb{G}_1 , i.e.,

$$H_2 : \{0, 1\}^* \rightarrow \mathbb{G}_1.$$

Asymmetric Encryption & Signature. The underlying public key encryption scheme of our protocol must be semantically secure (some well-known algorithms are RSA-OAEP [60], Paillier [61], and ElGamal [62]). We utilize elliptic curve versions of ElGamal encryption scheme due to the underlying algorithmic suits which need to work compatibly.

- $(pk_{\mathcal{U}}, sk_{\mathcal{U}})$ denotes a public key pair of a user \mathcal{U} (which is generated by a trusted third party (TTP)).
- $\text{AsymEnc}_{pk_{\mathcal{U}}}(M)$ denotes an encryption of a message M using the public key of the \mathcal{U} and $\text{AsymDec}_{sk_{\mathcal{U}}}(C)$ denotes a decryption of a ciphertext using the private key of \mathcal{U} .
- We denote $\text{Sign}_{sk_{\mathcal{U}}}(M)$ for the signature of a user \mathcal{U} using its private key $sk_{\mathcal{U}}$.

Note that the functionality Sign is the traditional PKI signature scheme such as Digital Signature Standard (DSS), American National Standard (ANS) X9.31, and Public Key Cryptography Standard (PKCS) #1.

Anonymous Public-Key Certificates for Secure Deduplication and Privacy-Preserving Public Auditing. Assume that a user \mathcal{A} uploads a file F to the CSP (in signed and encrypted form) and would like to get the services for both secure deduplication and public auditing. Assume also that another user \mathcal{B} has also the same file F and would like to upload to the CSP. However, the user \mathcal{B} should not send the file in encrypted or signed form, otherwise the client \mathcal{B} and the CSP would not be able to benefit communication and/or storage advantages. Still, the user \mathcal{B} should be able to delegate the auditing of the duplicated data without harming the privacy of the user \mathcal{A} . Namely, the TPA needs to verify the signatures without revealing the real identity of the user \mathcal{A} . Traditional PKI based architectures unfortunately cannot satisfy because of the inherent disclosure of the real identities.

We propose to use anonymous public-key certificates in our scheme to hide the real identities [17, 18, 20, 21]. In an anonymous public-key certificate architecture, the certificate issuing protocol allows a user to apply to certificate authorities for generating anonymous certificates using

a certificate already issued. Namely, pseudonyms will be in the anonymous certificate instead of the real identity of the users. Furthermore, in case of a malicious activity, an identity tracing protocol still enables a legal authority to trace the pseudonym in an anonymous certificate back to the real identity of the corresponding party. Note also that both Idemix [63] and uProve [64] offer complete anonymity even against to the certificate authorities. Furthermore, in case of a malicious user, their extensions can always extract the real identity of a user from an interaction with a relying party (by means of utilizing an external legal authority).

The Requests for Comments (RFC) document in [19] already defines a practical architecture to assure privacy of a user who requests and uses an X.509 certificate containing a pseudonym. This RFC document still provides the ability to link a certificate to the identity of the user who requested it.

We denote

$$\text{AnonymSign}_{sk_{\mathcal{U}}}(M)$$

for the signature of an anonymous user \mathcal{U} on a message M using its private key $sk_{\mathcal{U}}$. Our proposed mechanism can easily utilize the anonymous public-key certificate architecture of the RFC in [19].

Oblivious Pseudorandom Functions (OPRF). OPRF is a two-party protocol between a client C and a key server KS for privately computing a pseudorandom function $f_{k_{KS}}(x)$ where x is private key of C and k_{KS} is the private key of KS [65, 66]. At the end of the protocol, C obtains only $f_{k_{KS}}(x)$ while KS learns no information. More concretely, a functionality for the OPRF can be realized as

$$\mathcal{F}_{\text{OPRF}} : (k_{KS}, x) \rightarrow (\perp, f_{k_{KS}}(x))$$

for some pseudorandom function $f_{k_{KS}}$. Chaum’s *blind signatures* can be an example of OPRF [26, 38, 67].

4 Security Model

In this section, we aim at providing a security model for both privacy-preserving public auditing and secure deduplication.

4.1 Components

Our system involves five entities: A Certificate Authority (CA), a Key Server (KS), a CSP, a Trusted Party Auditor (TPA), and a user U_i . Their roles are described below:

- The CA is responsible for generating and issuing both traditional and anonymous public-key certificates. They are also responsible to trace the attackers back and identify their real identities (in case of a malicious activity). Note that this protocol is run only during the system setup.
- The KS and U_i run a two-party protocol OPRF. Note that this protocol is run only during the system setup.
- The CSP is a data storage owner which provides storage services for its clients to create, store, update and request data for retrievability. We assume that the CSP has a large storage, computation resources, and also provides host application services by the underlying virtual infrastructures. The users utilize these services in order to store and update their data in the CSP. Furthermore, the CSP supports secure client-side deduplication and privacy-preserving public auditing.

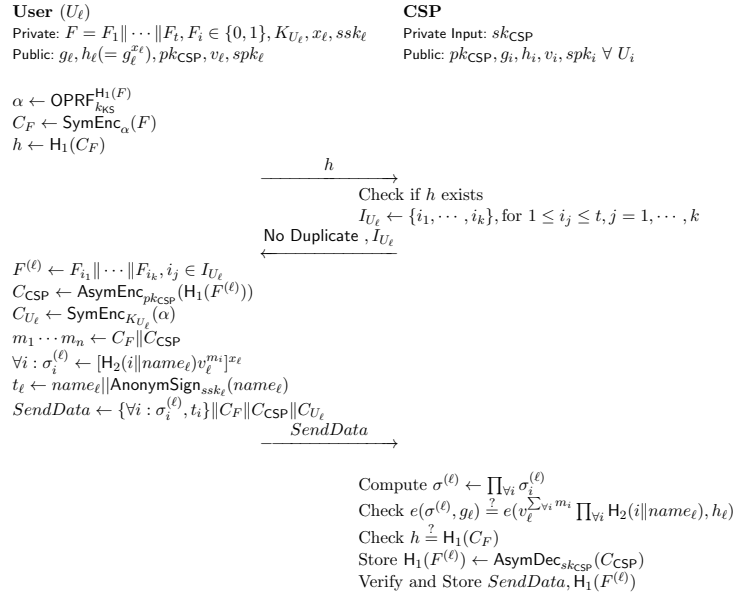


Fig. 4. The Scheme of Uploading a New File

- The user (U_i) is a client of the CSP and has large amount of data to be stored. Moreover, U_i utilizes the CSP's resources to store, retrieve, and share data with multiple users. U_i uploads her encrypted data to the CSP, and deletes the original one from the local storage. As for

auditing property, we assume that U_i delegates the integrity property to the TPA to verify that her data indeed stays in the CSP correctly.

- The TPA is assumed to be semi-honest. It can check the cloud storage reliability and validity of cloud storage. Furthermore, the TPA is assumed to have a secure connection with the CSP in order to check the integrity and validity of users' data. The TPA also assists users and the CSP to perform the duplication control and support secure deduplication.
- A key server KS is assumed to be semi-honest. An oblivious pseudo-random function is run between the KS and a user to realize a $\mathcal{F}_{\text{OPRF}}$.

4.2 Threat Model

First of all, TPA is assumed to be semi-honest, and all other components do not trust each other and are assumed to be malicious. Furthermore, we assume that the CA is trustworthy and do not collude with other components. The security of the proposed system is proven based on the CDH assumption in the random oracle model [68].

For designing a secure client-side deduplication scheme, we consider the following adversary types: (1) Malicious outside adversary, (2) Malicious insider adversary CSP, (3) Malicious cloud user adversary, and (4) Semi-honest adversary TPA.

- **Malicious outside adversary.** All the communication channels are assumed to be secure to maintain the confidentiality and integrity of the data being transferred (the communication channel between the cloud storage provider and the client can be secured by TLS (which is already an industry standard) while uploading or downloading files.). The outside adversary is also assumed to possess its hash value for later to fool the CSP and to pass the proof of ownership of the data.
- **Malicious insider adversary CSP.** We assume that the CSP is malicious which may arbitrarily deviate from the protocol and intends to modify or delete the users' encrypted data contents in order to gain extra information over the outsourced sensitive data. Moreover, the CSP may also try to build links between user profiles and accessed data files. We also assume that the CSP can always detect and learn the existence of a deduplication. Furthermore, since the CSPs already knows their clients (i.e., their real identities) they know which users share the duplicated data but do not disclose their real identities. However, they cannot learn any information about the duplicated data.

- **Malicious cloud user adversary.** The goal of a malicious user is to convince the CSP that he is indeed a legitimate data owner. We assume that the malicious adversary has the short hash of the data. This information can then be used as an input to be able to fool the CSP and pass the proof of ownership successfully.
- **Semi-honest adversary TPA.** The TPA is continuously executes the auditing scheme in a correct manner to assess the reliability of CSP on behalf of the users, but also tries to obtain some information about users' data.

We also assume that CSP and TPA are deployed by different organizations and they do not collude each other.

4.3 Security Goals

The proposed secure deduplication protocol with privacy-preserving public auditing model satisfies the following security objectives.

- **Public verifiability:** TPA can verify the correctness and the availability of the outsourced data without retrieving the entire data and without having online connections with the users.
- **Storage correctness:** A CSP can pass TPA's verification only if it indeed keeps the user's data.
- **Privacy:** No information about the outsourced data is leaked to TPA during the auditing process. Also, data itself is never leaked to the CSP except the information of duplication. Users' identities are also not disclosed when there is duplication.
- **Secure deduplication:** Secure deduplication is still possible on the CSP and does not leak any information to the CSP except the knowledge of duplication.

5 Our Secure Deduplication with Public Auditing Scheme

5.1 Setup

The following setup is based on Wang et al. [48] as we follow their secure auditing mechanism as a subalgorithm. The main difference is that the encrypted messages will be audited instead of its plaintext form and the underlying signature will be anonymous and they are verified as described above. We note that the scheme of Wang et al. [48] can adopt the use

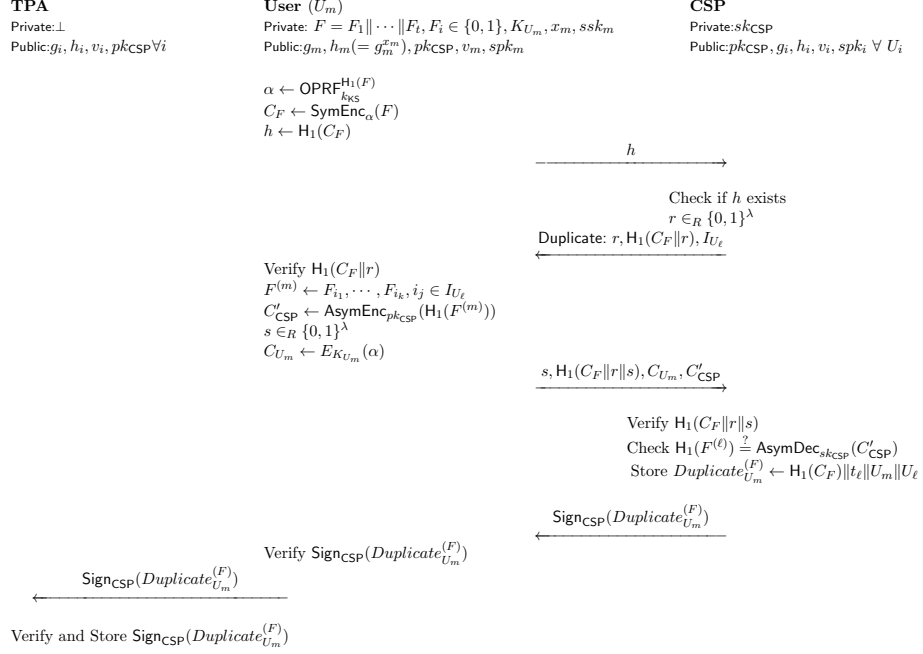


Fig. 5. The Scheme of Subsequent Upload

of the well-known optimization Merkle trees for proof of retrievability of very large files in an efficient manner (i.e., without having to read the entire file) [69].

First of all, a user U_i runs a key generation protocol and obtains public and private inputs as follows. The signing key pair (spk_i, ssk_i) is generated, and then the public key parameters of the user U_i is computed, denoted by

$$pk_i = \{spk_i, g_i, h_i, v_i, e(v_i, h_i)\}$$

where $x_i \in \mathbb{Z}_p$, $v_i \in \mathbb{G}_1$, $h_i = g_i^{x_i}$, and the private key of the user U_i is denoted by

$$sk_i = \{x_i, ssk_i\}.$$

Note that the public and private key pairs (pk_i, sk_i) of the i -th user is issued through an anonymous certificate protocol as described above (i.e., pseudonym is included in the certificate instead of the real identity). Furthermore, (pk_{CSP}, sk_{CSP}) denotes the public and private key pair of the CSP. Also, the CSP has the public keys g_i, h_i for all users U_i s. Similarly, the user U_i has also the public key of CSP denoted as pk_{CSP} and has also

the his file

$$F = F_1 \parallel \cdots \parallel F_t \text{ where } F_i \in \{0, 1\}, i = 1, \cdots, t.$$

K_{U_i} also denotes the (private) symmetric key of the user U_i .

Furthermore, an oblivious pseudorandom function (OPRF) protocol is run between a key server (KS) and a user in order to provide semantic security during encryption key generation where k_{KS} is the private key belongs to the KS (e.g., blind signature protocols).

5.2 Secure Data Upload Satisfying Deduplication with Public Auditing Scheme

The uploading algorithm is defined as follows (see Figure 4):

1. The ℓ -th user U_ℓ runs an OPRF protocol to compute $\alpha = \text{OPRF}_{k_{KS}}^{\text{H}_1(F)}$. Next, U_ℓ computes $C_F \leftarrow \text{SymEnc}_\alpha(F)$, $h \leftarrow \text{H}_1(C_F)$, and finally sends h to CSP.
2. The CSP checks whether h exists in the database. If it does not exist, it chooses a random set $I_{U_\ell} \leftarrow \{i_1, \cdots, i_k\}$ where $1 \leq i_j \leq t$, $j = 1, \cdots, k$, and returns **No Duplicate**, I_{U_ℓ} to the U_ℓ .
3. The U_ℓ first computes $F^{(\ell)} \leftarrow F_{i_1} \parallel \cdots \parallel F_{i_k}$ for $i_j \in I_{U_\ell}$. Note that $F^{(\ell)}$ is computed in order to ensure proof of retrievability (i.e., the data is available). Next, it encrypts it as $C_{\text{CSP}} \leftarrow \text{AsymEnc}_{pk_{\text{CSP}}}(\text{H}_1(F^{(\ell)}))$ and $C_{U_\ell} \leftarrow \text{SymEnc}_{K_{U_\ell}}(\alpha)$. Let $m_1 \cdots m_n \leftarrow C_F \parallel C_{\text{CSP}}$. For $i = 1, \cdots, n$, it computes $\sigma_i^{(\ell)} \leftarrow \text{AnonymSign}_{x_\ell}(\text{H}_2(i \parallel \text{name}_\ell) v_\ell^{m_i}) = [\text{H}_2(i \parallel \text{name}_\ell) v_\ell^{m_i}]^{x_\ell}$. Next, U_ℓ computes the file tag for $t_\ell \leftarrow \text{name}_\ell \parallel \text{AnonymSign}_{sk_\ell}(\text{name}_\ell)$ to ensure the integrity of the unique file identifier name_ℓ . Finally, it prepares $\text{SendData} \leftarrow \{\forall i : \sigma_i^{(\ell)}, t_i\} \parallel C_F \parallel C_{\text{CSP}} \parallel C_{K_\ell}$ and returns SendData to the CSP.
4. The CSP first computes $\sigma^{(\ell)} \leftarrow \prod_{\forall i} \sigma_i^{(\ell)}$ and checks the signatures by $e(\sigma^{(\ell)}, g_\ell) \stackrel{?}{=} e(v_\ell^{\sum_{\forall i} m_i} \prod_{\forall i} \text{H}_2(i \parallel \text{name}_\ell), h_\ell)$. Next, it also checks $h \stackrel{?}{=} \text{H}_1(C_F)$. If they are correct, it decrypts C_{CSP} by computing $\text{AsymDec}_{sk_{\text{CSP}}}(C_{\text{CSP}})$ and stores $\text{H}_1(F^{(\ell)})$. Finally, it verifies and stores $\text{SendData}, \text{H}_1(F^{(\ell)})$.

Remark 1. Note that, in the second round of the protocol, the cloud server searches the hash value h in the database and decides whether the encrypted file C_F is in the database. The security of this solution is based on collision-resistant hash functions $\text{H}_1(\cdot)$. However, if malicious users

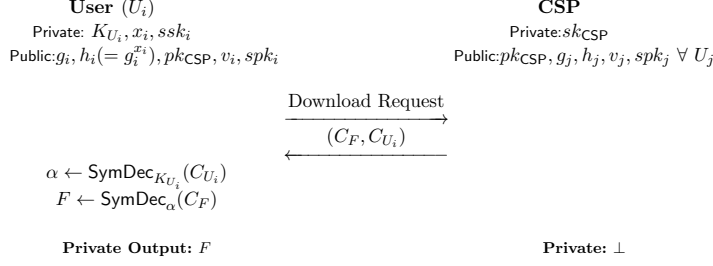


Fig. 6. The Scheme of Data Retrieval

somehow obtain or compute collisions in practice then only looking for h become not sufficient. Namely, if the malicious users somehow has the short hashes h then they could fool the CSP that they indeed have the encrypted file C_F s. Therefore, in the third round of our protocol, we additionally request $F^{(\ell)}$ to eliminate these threats and to ensure the proof of correctness and retrievability.

5.3 The Scheme of Subsequent Upload

The following algorithm is executed if there is duplicate file on the CSP (see Figure 5):

1. The m -th user U_m runs an OPRF protocol to compute $\alpha \leftarrow \text{OPRF}_{k_{KS}}^{\text{H}_1(F)}$. Next, U_m computes $C_F \leftarrow \text{SymEnc}_\alpha(F)$, $h \leftarrow \text{H}_1(C_F)$, and finally sends h to CSP.
2. The CSP checks whether h exists in the database. If it exists, it chooses a random number $r \in_R \{0, 1\}^\lambda$ and returns **Duplicate:** $r, \text{H}_1(C_F \| r), I_{U_\ell}$. Note that $r, \text{H}_1(C_F \| r)$ is sent to prove the possession of C_F to the U_m . Similarly, the index set I_{U_ℓ} is sent to prove that the user indeed possess the file F .
3. The U_m first verifies $\text{H}_1(C_F \| r)$ to ensure that the CSP indeed possess the C_F . Next, it computes $F^{(m)} \leftarrow F_{i_1}, \dots, F_{i_k}, C'_{CSP} \leftarrow \text{AsymEnc}_{pk_{CSP}}(\text{H}_1(F^{(m)}))$. As described in Remark 1 for the protocol in Figure 4, the goal of sending $F^{(m)}$ is to guarantee the proof of retrievability of the encrypted file C_F (i.e., data is indeed on the client-side). Next, it chooses random number $s \in_R \{0, 1\}^\lambda$ and computes $C_{U_m} \leftarrow E_{K_{U_m}}(\alpha)$. Finally, it sends $s, \text{H}_1(C_F \| r \| s), C_{U_m}, C'_{CSP}$. Similarly as in the previous round, s and $\text{H}_1(C_F \| r \| s)$ are sent to prove that the U_m indeed possess C_F . Also, C'_{CSP} proves the possession of F .

4. The CSP verifies $H_1(C_F || r || s)$ and checks $H_1(F^{(\ell)}) \stackrel{?}{=} \text{AsymDec}_{sk_{\text{CSP}}}(C'_{\text{CSP}})$, and stores $\text{Duplicate}_{U_m}^{(F)} \leftarrow H_1(C_F) || t_\ell || U_m || U_\ell$. Finally, it returns $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ to U_m . This signature assures the user that the data is linked with the U_m . Also, it prevents a malicious CSP (the signer) from denying the signing. Note that the users' pseudonyms are used instead of their real identities.
5. The U_m verifies the signature $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ and forwards it to TPA.
6. The TPA verifies and stores $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$. Note that TPA will process the auditing utilizing the signatures of U_ℓ on behalf of U_m . Because the signatures are anonymous no one will know any information about the real identity of U_ℓ .

Remark 2. We highlight that one needs to store the CSP's signatures $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ for later auditing processing since otherwise one cannot later convince CSP that the deduplication was already occurred between the specific anonymous users. Therefore, in our proposal, the CSP sends these signatures to the users which forwards them to the TPA. We highlight that, unlike the existing auditing mechanisms, the TPAs in our proposal are not stateless (memoryless). In case of utilizing a stateless TPA, a local copy of these signatures should be copied on the user side (instead of forwarding to the TPA). However, in that case, the user must always forward these signatures to the TPA before it can start the auditing process.

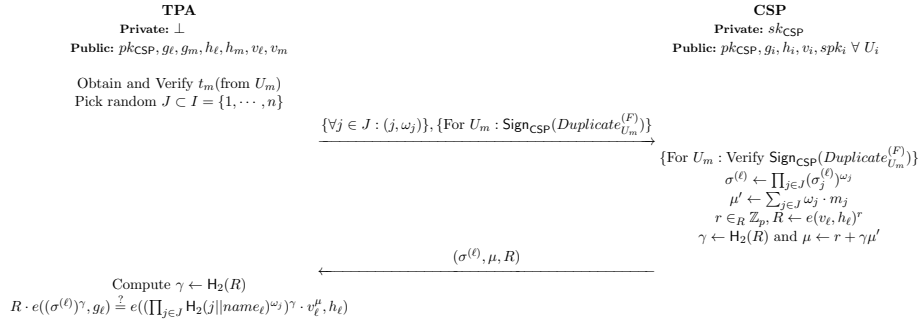


Fig. 7. Privacy-Preserving Public Auditing Scheme

Charging each client in the case of deduplication. In practice, cloud providers typically charge its clients based on the amount of data they stored. We would like to highlight that anonymous certificates are only used for duplicated users and cloud storage providers can identify their clients in our mechanism since there is already an authentication protocol between each client and the storage provider. Therefore, it is easy for a cloud provider to charge each client if there is already a deduplication.

5.4 The Scheme of Data Retrieval

Our data retrieval protocol is as follows (see Figure 6): the user U_m sends a download request from CSP and receives (C_F, C_{U_i}) . Next, U_m then computes the encryption key $\alpha \leftarrow \text{SymDec}_{K_{U_i}}(C_{U_i})$ and obtains the file by computing $F \leftarrow \text{SymDec}_\alpha(C_F)$.

5.5 Privacy-Preserving Public Auditing Scheme

The privacy of our auditing mechanism follows from the Wang et al.'s scheme [48] (see Figure 7). First of all, the TPA obtains the tags t_i (including the m -th user U_m) and verifies their signatures. If they are correct, the TPA next picks a random proper subset of $J \subset I = \{1, \dots, n\}$ and for all $j \in J$, it sends (j, ω_j) to the CSP. Note that if the TPA audits on behalf of the user U_m then it also sends $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$, where $\text{Duplicate}_{U_m}^{(F)} = \text{H}_1(C_F) \| t_\ell \| U_m \| U_\ell$ (because of the existence of the duplication). Note that these signatures ensure the CSP that there was a deduplication with the user U_ℓ , and in this case, the CSP needs to send necessary auditing information of the U_ℓ .

The CSP first verifies the signatures and then computes $\sigma^{(\ell)} \leftarrow \prod_{j \in J} (\sigma_j^{(\ell)})^{\omega_j}$, $\mu' \leftarrow \sum_{j \in J} \omega_j \cdot m_j$, and for random $r \in_R \mathbb{Z}_p$ it computes $R \leftarrow e(v_\ell, h_\ell)^r$. Next, the CSP computes $\gamma \leftarrow \text{H}_2(R)$ and $\mu \leftarrow r + \gamma \mu'$ and sends $\sigma^{(\ell)}, \mu, R$ back to the TPA. The TPA first computes $\gamma \leftarrow \text{H}_2(R)$ and then verifies $R \cdot e((\sigma^{(\ell)})^\gamma, g_\ell) \stackrel{?}{=} e((\prod_{j \in J} \text{H}_2(j \| \text{name}_\ell)^{\omega_j})^\gamma \cdot v_\ell^\mu, h_\ell)$.

6 Security Analysis

In this section, we prove that our proposed protocols in Section 5 satisfy the security model defined in Section 4.

In the following proof, we start by constructing a probabilistic polynomial-time simulator that produces a protocol transcript which is statistically

indistinguishable from the one resulting from a real execution of the authentication protocol [70]. Namely, given a corrupted party (either a user U_ℓ or the CSP), we construct an efficient simulator that has access to the public and private input of the corrupted party before the simulation is run and produces a view which is statistically indistinguishable from the view of that party interacting with the other honest party.

Theorem 1. *Assume that OPRF used is secure, H_1, H_2 are hash functions modeled as random oracles, and the CDH problem is hard. Then, our protocol in Figure 4 securely uploads a file F in the presence of malicious adversaries.*

Proof. The security proof of the protocol is shown in the OPRF-hybrid model, where the user and SF are assumed to have access to a trusted party computing the OPRF functionality following the ideal model of our definition. Thus, the simulator will play the trusted party in the OPRF, when simulating for the adversary.

We separately consider the different corruption cases (when no parties are corrupted, and when either one of the parties is corrupted). In the case that no parties are corrupted, the security reduces to the semi-honest case.

Assume that the user U_ℓ is corrupted: In this case, the simulator \mathcal{A} has the sk_{CSP} apart from the public parameters. First of all, the \mathcal{A} arbitrarily a set I_{U_ℓ} . \mathcal{A} then sends the I_{U_ℓ} to the user and obtains $SendData$. The simulator \mathcal{A} then computes $\sigma^{(\ell)} \leftarrow \prod_{\forall i} \sigma_i^{(\ell)}$ and checks the signatures by $e(\sigma^{(\ell)}, g_\ell) \stackrel{?}{=} e(v_\ell^{\sum_{\forall i} m_i} \prod_{\forall i} H_2(i || name_\ell), h_\ell)$. Next, it also checks $h \stackrel{?}{=} H_1(C_F)$. If they are correct, it simulates $AsymDec_{sk_{CSP}}(C_{CSP})$ since it knows the C_{CSP} , the encrypted message $AsymEnc_{pk_{CSP}}(C_{CSP})$, and pk_{CSP} .

Assume that the CSP is corrupted: In this case, the simulator \mathcal{A} has the private values of the user U_ℓ , i.e., $F, K_{U_\ell}, x_\ell, ssk_\ell$. The \mathcal{A} first arbitrarily chooses a file F and calls the ideal functionality OPRF and learns $\alpha = OPRF_{k_{KS}}^{H_1(F)}$. Next, \mathcal{A} computes $C_F \leftarrow SymEnc_\alpha(F)$, $h \leftarrow H_1(C_F)$, and finally sends h to CSP. Upon receiving No Duplicae and I_{U_ℓ} , the \mathcal{A} computes $F^{(\ell)} \leftarrow F_{i_1} || \dots || F_{i_k}$ for $i_j \in I_{U_\ell}$. Next, it encrypts it as $C_{CSP} \leftarrow AsymEnc_{pk_{CSP}}(H_1(F^{(\ell)}))$ and $C_{U_\ell} \leftarrow SymEnc_{K_{U_\ell}}(\alpha)$. Let $m_1 \dots m_n \leftarrow C_F || C_{CSP}$. For $i = 1, \dots, n$, it computes $\sigma_i^{(\ell)} \leftarrow AnonymSign_{x_\ell}(H_2(i || name_\ell) v_\ell^{m_i}) = [H_2(i || name_\ell) v_\ell^{m_i}]^{x_\ell}$. Next, the \mathcal{A} computes the file tag for $t_\ell \leftarrow name_\ell || AnonymSign_{ssk_\ell}$ to ensure the integrity of the unique file identifier $name_\ell$. Finally, it prepares $SendData \leftarrow \{\forall i : \sigma_i^{(\ell)}, t_i\} || C_F || C_{CSP} || C_{K_\ell}$ and returns $SendData$ to the CSP.

The transcript of the view of both parties is simulated, and it is consistent and statistically indistinguishable when interacting with the honest verifier.

	CSP			Client Side			TPA		
	# Pairing	# EC Multiplication	# Asymmetric Enc/Sign	# Pairing	# EC Multiplication	# Asymmetric Enc/Sign	# Pairing	# EC Multiplication	# Asymmetric Enc/Sign
The Scheme of Uploading a New File (Figure 4)	2	1	1 AsymDec	0	$2n$	1 $\text{OPRF}_{k_{KS}}^{\mathcal{H}_1(F)}$ 1 AsymEnc 1 Anonym-Sign	NA	NA	NA
The Scheme of Subsequent Upload (Figure 5)	0	0	1 Sign 1 AsymDec	0	0	1 $\text{OPRF}_{k_{KS}}^{\mathcal{H}_1(F)}$ 1 AsymEnc	0	0	0
The Scheme of Data Retrieval (Figure 6)	0	0	0	0	0	0	NA	NA	NA
Privacy-Preserving Public Auditing Scheme (Figure 7)	0	$ J + 1$	0	NA	NA	NA	2	$ J + 3$	0

Table 1. Computational Complexity of the Proposed Scheme. NA denotes “Not Applicable”, n denotes the number of blocks of the message $C_F || C_{\text{CSP}}$, and $J \subset I = \{1, \dots, n\}$. Note that, for the sake of easy notation, we use multiplicative notation for elements of \mathbb{G}_1 , \mathbb{G}_2 , and \mathbb{G}_3 in our protocol descriptions.

Theorem 2. *Assume that H_1 is a hash function modeled as a random oracle and the CDH problem is hard. Then, our protocol for the subsequent upload in Figure 5 is secure against malicious users (uploaders) and malicious outside attackers.*

Proof. We provide a formal proof via the formal verification tool Scyther [71, 72] to ensure the proof of possession of C_f and that a malicious user cannot get any information during the secure deduplication part of the protocol in Figure 5. Before we give a formal proof, we would like to briefly sketch the idea on the proof: the objective of the malicious uploader to compromise the confidentiality of data uploaded by legitimate users. In particular, the goal of an adversary is to convince the CSP that it possesses a pre-stored data. The proof of possession and the proof of retrievability are given by the first three rounds of the protocol. Namely, proving the knowledge of $F^{(m)}$ indeed guarantees that the file F is available on the client-side. Informally speaking, in the first step, an adversary U_{adv} obtains the hash of the encrypted data. U_{adv} then sends the hash

	Efficient Realizability (in terms of Deduplication and Auditing)	Privacy-Preserving Public Auditing
Alkhojandi and Miri [22]	\times (Loss of deduplication advantages)	\times
Li et al. [23]	\times (Loss of bandwidth advantages)	\times (achieves weak privacy since the file is uploaded to the TPA)
This paper	\checkmark	\checkmark

Table 2. Comparison with the Existing Schemes.

of encrypted data which only allows him to learn whether there is deduplication. If there is a deduplication, the CSP challenges the adversary to assure the possession of data via $r, H_1(C_F||r), I_{U_i}$ for some i . Note that because of the underlying secure hash function (in the random oracle model) the adversary cannot upload a fake data (which compromises the integrity of data) and it does not give any sensitive information to the adversary. The adversary has to return $H_1(C_F||r||s), C_{U_{adv}}$ which is only possible if the adversary possess the data F . The CSP can only be ensured if the verifications are passed successfully. Hence, the adversary cannot link himself to a legitimate data without possessing it.

The formal proof via a formal verification tool Scyther [71,72] is given in Appendix A. The modeling of this part is given in a language called is Security Protocol Description Language (SPDL) in Appendix A including the codes of the validation of the protocol specifications. In this way, we show that no malicious adversary can get a valuable information during the deduplication part of the protocol.

If the proof of possession of the ciphertext C_f is guaranteed then the user must ensure the knowledge of the message $F^{(m)}$ by checking $H_1(F^{(\ell)}) \stackrel{?}{=} \text{AsymDec}_{sk_{\text{CSP}}}(C'_{\text{CSP}})$. Furthermore, the signature $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ links anonymously the U_ℓ with the U_m . Furthermore, the CSP returns $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ to the U_m which forwards it to the TPA. Because the signatures are anonymous no one will know any information about the real identity of U_ℓ . Hence, the proposed protocol is secure against malicious adversaries.

Theorem 3. *Our protocol for the data retrieval in Figure 6 is secure against malicious users (uploaders) and malicious outside attackers.*

Proof. It is trivial to show that the data retrieval protocol does not lead to a security breach because the only value that the CSP sends are the encryptions C_F and C_{U_i} . That is, since the adversary does not know the symmetric key of the encryptions it cannot get any information about the data.

Theorem 4. *Assume that H_2 is a hash function modeled as a random oracle and the CDH problem is hard. Then, our protocol for the privacy-preserving public auditing in Figure 7 is secure against semi-honest TPAs and malicious CSPs.*

Proof. First of all, the TPA obtains the tags t_i and verifies their corresponding signatures. If they are correct, the TPA next picks a random proper subset of $J \subset I = \{1, \dots, n\}$ and for all $j \in J$, it sends (j, ω_j) to the CSP to start the auditing process. The security, the privacy-preserving public verifiability, and the storage correctness against corrupted TPAs and CSPs basically follow the underlying auditing mechanisms of Wang et al. [48]. Note that the proof of Wang et al. only ensures the integrity of the data and do not hide the identity of the users. In our scheme, if the TPA audits on behalf of the user U_m then it also must send $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$, where $\text{Duplicate}_{U_m}^{(F)} = H_1(C_F) \| t_\ell \| U_m \| U_\ell$. Note that these signatures ensure that there is a deduplication with the user U_ℓ , and in this case, the CSP needs to send necessary auditing information of the U_ℓ . On the one hand, the signatures $\text{Sign}_{\text{CSP}}(\text{Duplicate}_{U_m}^{(F)})$ assures the user U_m that her data is linked to the user U_ℓ , and therefore, it prevents a malicious CSP (the signer) from denying the signing (i.e., assures *non-repudiation*). On the other hand, they prevent malicious users from claiming false duplications.

Furthermore, the privacy of users during the auditing process is guaranteed by the underlying anonymous public-key certificates, i.e., users' pseudonyms are used in the signatures instead of their real identities. In the case of a malicious activity, the CA can also easily trace the malicious users back and can detect their real identities.

Hence, the modified version of the auditing scheme provides both secure deduplication privacy of users simultaneously.

7 Complexity Analysis

In Table 1, we provide the number of pairings, Elliptic Curve (EC) multiplications, and Asymmetric operations (in terms of public key encryption

and signatures) of our system. The comparison has been given for the user, the CSP, and the TPA separately.

Furthermore, in Table 2, we compare our protocol with the only existing protocols of [22] and [23] which aim to satisfy public auditing and secure deduplication simultaneously. Note that the main drawback of [22] is that deduplication is performed by an mediator within the enterprise. Therefore, not many deduplication would occur on a small size of enterprises instead of performing deduplication on the large CSPs.

On the other hand, the main drawback of [23] is that the file is uploaded to the semi-honest TPA in plaintext form. Therefore, privacy will not be achieved against malicious TPAs. And more importantly, client-side deduplication solution of [23] would not eliminate the bandwidth advantage for a user. We also note that the protocol of [23] is also too inefficient because for a secure implementation one needs supersingular elliptic curves over large prime fields (see for further details [24]).

8 Conclusion

In this paper, we proposed a solution for the dilemma where the CSPs are willing to use deduplication to save communication and storage costs while the users are willing to encrypt their data before uploading and also to ensure that their data has never been modified without being detected. In this respect, we propose an efficient solution in order to fulfill privacy-preserving data integrity and secure duplication simultaneously. We prove the security of the proposed scheme in the random oracle model, assuming that the CDH problem is hard. We leave open the question of constructing efficient cryptographic protocols that do not need certificate authorities or anonymous certificates.

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A Formal Security Analysis Using Scyther

A.1 Security Protocol Description Language (SPDL) Code

Because it is very effective for finding errors, its modeling adversaries with different capabilities, and it is easy to implement the protocol we chose Scyther [71, 72] as an automatic evaluation tool.

```

# C-f is modeled as k(I,R) because of private shared information

hashfunction h;

protocol hashed-protocol(I,R) {

  role I {

    var r: Nonce;
    fresh s: Nonce;

    send_1(I, R, h(k(I,R))); # U_m sends H.1(C-f) to CSP
    recv_2(R, I, r, h(k(I,R), r)); # CSP sends r, H.1(C-f||r) to U_m
    send_3(I, R, s, h(k(I,R), r, s) ); # U_m sends s, H.1(C-f||r||s) to CSP

    claim_i1(I, Niagree); # checks the integrity of the transmitted data
    claim_i2(I, Secret, k(I,R)); # checks the confidentiality of the data

  }

  role R {

    fresh r: Nonce;
    var s: Nonce;

    recv_1(I, R, h(k(I,R)));
    send_2(R, I, r, h(k(I,R), r));
    recv_3(I, R, s, h(k(I,R), r, s) );

    claim_r1(R, Niagree); # checks the integrity of the transmitted data
    claim_r2(R, Secret, k(I,R)); # checks the confidentiality of the data

  }
}

```

A.2 Output of the above code is as follows

In Figure 8, Scyther's output ensures that that no information is leaked during the protocol.

The image shows a window titled "Scyther: dedup.spdl" with a menu bar (File, Verify, Help) and two tabs: "Protocol description" and "Settings". The "Protocol description" tab contains the following code:

```

1 # C_f is modeled as k(I,R) because of private shared information
2
3 hashfunction h;
4
5 protocol hashed-protocol(I,R) {
6
7 role I {
8
9 var r: Nonce;
10 fresh s: Nonce;
11
12 send_1(I, R, h(k(I,R))); # U_m sends h to CSP
13 rcv_2(R, I, r, h(k(I,R), r)); # CSP sends r, H(C_f||r) to U_m
14 send_3(I, R, s, h(k(I,R), r, s)); # U_m sends s, H(C_f||r||s) to CSP
15
16 claim_1(I, Niagree); # checks the integrity of the transmitted data
17 claim_2(I, Secret, k(I,R)); # checks the confidentiality of the data
18
19 }
20
21 role R {
22
23 fresh r: Nonce;
24 var s: Nonce;
25
26 rcv_1(I, R, h(k(I,R)));
27 send_2(R, I, r, h(k(I,R), r));
28 rcv_3(I, R, s, h(k(I,R), r, s));
29
30 claim_r1(R, Niagree); # checks the integrity of the transmitted data
31 claim_r2(R, Secret, k(I,R)); # checks the confidentiality of the data
32

```

Overlaid on the bottom right of the window is a smaller window titled "Scyther results : verify". It contains a table with the following data:

Claim	Status	Comments
hashed_protocol I hashed_protocol,i1 Niagree	Ok Verified	No attacks.
hashed_protocol,i2 Secret k(I,R)	Ok Verified	No attacks.
R hashed_protocol,r1 Niagree	Ok Verified	No attacks.
hashed_protocol,r2 Secret k(I,R)	Ok Verified	No attacks.

Below the table, the text "Done." is displayed.

Fig. 8. Scyther's output