Achieving Efficient and Privacy-Preserving Multi-Domain Big Data Deduplication in Cloud

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Abstract—Secure data deduplication, as it can eliminate redundancies over encrypted data, has been widely developed in cloud storage to reduce storage space and communication overheads. Among them, the convergent encryption has been extensively adopted. However, it is vulnerable to brute-force attacks that can determine which plaintext in a message space corresponds to a given ciphertext. Many existing schemes have to sacrifice efficiency to resist brute-force attacks, especially for cross-domain deduplication, which is inevitably contrary to practical applications. Moreover, few existing schemes consider protecting the message equality information (i.e., whether two different ciphertexts correspond to an identical plaintext). To address the above challenges, in this paper, we propose an efficient and privacy-preserving big data deduplication scheme for a two-level multi-domain architecture. Specifically, by generating a random tag and a constant number of random ciphertexts for each data, our scheme not only ensures data confidentiality under multi-domain deduplication but also resists brute-force attacks. By allowing only the agent and cloud service provider to perform intra-deduplication and inter-deduplication, respectively, our scheme can protect the message equality information from disclosure as much as possible. Detailed security analysis shows that our scheme achieves privacy-preservation for both data content and the message equality information and data integrity while resisting brute-force attacks. Furthermore, extensive simulations demonstrate that our scheme significantly outperforms the existing competing schemes, especially the computational cost and the time complexity of the duplicate search.

Index Terms—Secure data deduplication, cross-domain deduplication, brute-force attacks, message equality information.

1 INTRODUCTION

U
der big data-driven society, data deduplication technique [1] has been widely developed in cloud storage because it can significantly reduce storage costs by storing only a single copy of redundant data. Indeed, data deduplication can reduce storage costs by more than 50% in standard file systems and by more than 90% for backup applications, and these savings translate into substantial financial savings to cloud service providers and users [2]. However, considering security and privacy concerns of outsourced data, users are likely to encrypt data with their own keys before outsourcing. This impedes the cross-user deduplication since an identical data will be encrypted into different ciphertexts by different users’ keys, i.e., it is challenging to identify duplicates over different ciphertexts. Thus, how to efficiently conduct data deduplication over encrypted data becomes a pressing issue.

Convergent encryption [3] provides the first viable solution to allow deduplication on encrypted data, which is formalized as the message-locked encryption later in [4]. It encrypts the data with the convergent key derived by computing the cryptographic hash value of the data itself. Since the encryption is a deterministic symmetric encryption algorithm, identical data will generate the same convergent key and ciphertext, which achieves deduplication on encrypted data. However, the convergent encryption is vulnerable to brute-force attacks due to its deterministic property [5]. To resist such attacks, some server-aided encryption schemes [5], [6], [7] have been presented. In these schemes, a domain or tenant (e.g., a company or university) deploys a dedicated key server to help affiliated users to generate the convergent key and the corresponding tag through an interactive protocol. Unfortunately, since key servers in different domains randomly select different secret keys, cross-domain deduplication is infeasible, which dramatically reduces the effectiveness of data deduplication. To support cross-domain deduplication, an inter-deduplication algorithm has recently been constructed [8]. Since only the encrypted data uploaded by the first user will be stored in the cloud, to ensure that the encrypted data can be correctly decrypted by users with ownership, the number of generated ciphertexts is linear with the number of domains. Thus, the scalability issue will inevitably arise when the number of domains explodes, which will lead to massive computational and communication overheads for users and the cloud service provider.

Moreover, the message equality information of outsourced data (i.e., the information about whether two different ciphertexts correspond to an identical plaintext) may also leak the content of encrypted data to some extent [2]. Although this information disclosure is inevitable in data deduplication, we hope to minimize such information leakage. Recently, two solutions [9], [10] have been drawn to achieve this goal. The crux of both schemes is to permit only the deduplication operator to know such information. The first scheme [9] employs an additional trusted server to complete the duplicate verification. However, the assumption that the trusted server is always online and will not be compromised is too strong to be accepted in practice [11]. The second scheme [10]
seems a good candidate because it protects the message equality information by introducing a technical method rather than an additional trusted server. Besides, this scheme efficiently achieves cross-domain deduplication and resists brute-force attacks at the same time. Unfortunately, this scheme can only support the cross-domain deduplication for two different domains.

As described in [12], secure cross-domain (or cross-user) deduplication schemes are evaluated in terms of two factors: security properties that each scheme provides and system overheads incurred on the cloud service provider and users. However, as far as we know, existing related schemes cannot efficiently achieve the strong confidentiality of outsourced data while resisting brute-force attacks. Thus, in this paper, under the similar two-level multi-domain architecture [8], [10], we propose an efficient and privacy-preserving multi-domain big data deduplication scheme in cloud storage. The main contributions of this paper are three aspects:

- First, we propose a secure multi-domain deduplication scheme that can support data deduplication not only in the same domain (called intra-deduplication) but also across multiple different domains (called inter-deduplication). Specifically, the proposed scheme generates the random convergent key and the random tag based on the bilinear pairing technique [13] to ensure data confidentiality. The proposed scheme only needs to produce a constant number of random ciphertexts to ensure that the outsourced encrypted data can be correctly decrypted by users with ownership. Moreover, the proposed scheme achieves that only the cloud service provider can perform the inter-deduplication by comparing random inter-tags derived from the Boneh-Goh-Nissim cryptosystem [14].
- Second, to improve the time complexity of duplicate search, we construct a deduplication decision tree based on the B+ tree [15], which works well for the big data storage system. In particular, the length of plaintext can be used to represent the keyword in the B+ tree.
- Third, we analyze the security of the proposed scheme and demonstrate that it can achieve strong data confidentiality and data integrity while resisting brute-force attacks. Besides, extensive performance evaluations justify the efficiency of the proposed scheme in terms of computational, communication and storage overheads.

The remainder of this paper is organized as follows. We will introduce the system model, threat model and design goals in Section 2, before recalling bilinear groups of composite order, the Boneh-Goh-Nissim cryptosystem and B+ tree in Section 3. Then, we present our scheme in Section 4, followed by its security analysis and performance evaluation in Sections 5 and 6, respectively. Related work is discussed in Section 7. We conclude our work in Section 8.

2 MODELS AND DESIGN GOALS

In this section, we formalize the system model and threat model used in this paper, and identify our design goals.

2.1 System Model

Similar to [8], [10], our system is a two-level multi-domain deduplication model, which provides the intra-deduplication and inter-deduplication. More specifically, the first level contains a number of domains \( D = \{D_1, D_2, \ldots, D_n\} \). Each domain \( D_i \), corresponding to an organization (e.g., an enterprise or a university) contains a group of affiliated users (e.g., staff in an enterprise or faculty and students in a university) and employs an agent to complete the intra-deduplication. The second level includes a cloud service provider, which conducts the inter-deduplication. Besides, a key distribution server is introduced to set up the system. Fig. 1 illustrates the system architecture of the proposed scheme and the details of each entity are described as follows.

- Key distribution server (KDS): The KDS is responsible for generating different private keys for users from different domains and a secret for the cloud service provider to perform the inter-deduplication.
- Cloud service provider (CSP): The CSP offers storage services for users. Although the CSP seems to have abundant storage space, the corresponding costs of the management and maintenance for big data are relatively expensive. Hence, the CSP prefers to conduct the inter-deduplication over outsourced data from all domains to save costs by storing only one copy.
- Users: Users from the same domain receive the same private key from the KDS, on the contrary, users from different domains possess different private keys. Based on the received private key, users can generate a random convergent key used for encrypting the data and an intra-tag used for deduplicating.
- Agent \((A_i)\): In order to improve the efficiency of duplication search and resist an online brute-force attack launched by malicious users, an agent \(A_i\) located between users and the CSP is hired by \(D_i\) for performing intra-deduplication and transforming a random intra-tag into a random inter-tag.

The overall workflow is roughly described as follows. When a user \(U\) from \(D_i\) wants to upload data \(m\), \(U\) generates a random intra-tag and sends it to \(A_i\). Then, \(A_i\) performs the intra-deduplication based on the received intra-tag. If a duplicate is found, \(A_i\) returns the corresponding feedback. Otherwise, \(A_i\) transforms the intra-tag into a random inter-tag and sends it to the CSP for inter-deduplication. Note that only when the CSP does not find a duplicate, \(U\) needs to encrypt \(m\) and upload the corresponding ciphertext.

![Fig. 1: System model under consideration](image-url)
only participates in system setup. Similar to the existing literature dealing with the security in cloud storage [16], [17], the CSP and $A_i$, considered as honest-but-curious, will honestly follow the underlying scheme, but are curious about contents of outsourced encrypted data. Specifically, based on the background knowledge about the plaintext space, the CSP would collude with $A_i$ to guess the content of a targeted ciphertext by launching an offline brute-force attack. Furthermore, the encrypted data stored in the CSP may be altered due to physical failures [18], [19] or monetary reasons [20].

Similar to [8], users are also assumed to be honest-but-curious. Concretely, they will not frame the CSP or corresponding $A_i$ by uploading invalid data. However, they may be interested in obtaining the content of encrypted data without ownership. Besides, if a malicious user (corrupted by the adversary) knows the plaintext space, he/she would try to launch an online brute-force attack by repeatedly executing the data upload procedure to guess the content of the targeted ciphertext. Note that users would not collude with the CSP or $A_i$ due to their own privacy concerns and the reputation of the CSP or $A_i$ [21].

Besides, we assume that the users from $D_i$ connect with the corresponding agent $A_i$ and all agencies connect with the CSP through secure channels.

2.3 Design Goals

Based on the threat model, we intend to achieve the following goals in the proposed scheme:

- **Data confidentiality.** There exist two kinds of data confidentiality in our model. One is related to the semantic security of encrypted data and tags, i.e., any adversary even corrupting the CSP or $A_i$, or unauthorized users cannot feasibly extract any information about a plaintext from its ciphertext or tag. The other is related to the message equality information, i.e., any adversary excluding the CSP ($A_i$) cannot decide whether two given tags from different domains (the same domain $D_i$) correspond to the same data or not.

- **Data integrity.** In the design of secure data deduplication, only one copy will be stored in the CSP. Since this unique copy may be altered due to some physical failures or monetary reasons, the proposed scheme should provide data integrity to ensure that users can verify whether the downloaded data are modified or not.

- **Brute-force attack resistance.** With the background knowledge of the plaintext space, any adversary even corrupting the CSP or $A_i$ cannot determine which plaintext corresponds to a specific tag and ciphertext through an offline brute-force attack. It is worth noting that the CSP or $A_i$ can determine whether two ciphertexts correspond to the same plaintext by comparing received tags, but they cannot determine which plaintext in the plaintext space corresponds to these ciphertexts. Besides, the malicious user (corrupted by the adversary) tries to guess the content of the targeted ciphertext by launching online brute-force attacks. Thus, the proposed scheme should also try to resist such attacks.

- **Efficiency.** Apart from security requirements, efficiency is the most important metric for data deduplication [16]. Actually, applying secure deduplication would lead to some unavoidable costs for users and the CSP [12], e.g., tag generation, duplication search, and verification. Therefore, achieving the efficiency of computational, communication and storage overheads is also our design goal, especially in today’s big data-driven society. Meanwhile, facing a vast volume of data, the time complexity of duplication search should be reduced as much as possible.

3 PRELIMINARIES

In this section, we outline the bilinear groups of composite order [13], Boneh-Goh-Nissim cryptosystem [14] and B+ tree [15], which will serve as the basis of the proposed scheme.

3.1 Bilinear Groups of Composite Order

Given a security parameter $\kappa$, a composite bilinear parameter generator $Gen(\kappa)$ outputs a tuple $(p,q,G,G_T,e)$, where $p$ and $q$ are two $\kappa$-bit primes, $G$ and $G_T$ are two finite cyclic multiplicative groups of composite order $N = pq$, and $e : G \times G \rightarrow G_T$ is a bilinear map with the following properties:

- **Bilinear:** $e(x^a,y^b) = e(x,y)^{ab}$ for all $x, y \in G$, and $a, b \in \mathbb{Z}_N$.
- **Non-degeneracy:** If $g$ is a generator of $G$, then $e(g, g)$ is a generator of $G_T$ with the order $N$.
- **Computability:** For all $x, y \in G$, there exists an efficient algorithm to compute $e(x, y) \in G_T$.

Some related complexity assumptions are given below. For more comprehensive descriptions, refer to [22], [23].

**Definition 1.** (Computational Diffie-Hellman (CDH) Problem). The CDH problem in $G$ is defined as follows: Given $g, g^a, g^b \in G$ for unknown $a, b \in \mathbb{Z}_N$, compute $g^{ab} \in G$.

**Definition 2.** (The $n$-th Bilinear Diffie-Hellman Exponent (n-BDHE) problem). The n-BDHE problem is: given a vector of $2n+1$ elements $(h, g, g^a, g^{a^2}, \ldots, g^{a^{n+2}}, \ldots, g^{a^{2n}}) \in G^{2n+1}$ for unknown $\alpha \in \mathbb{Z}_N$, compute $e(g, h)\alpha^{n+1} \in G_T$.

It is worth noting that the input vector is missing the term $g^{a^{n+1}}$ so that the bilinear map seems to be of little help in computing the required $e(g, h)\alpha^{n+1}$.

**Definition 3.** (Decisional n-BDHE problem). The decisional n-BDHE problem is stated as follows: given $(2n + 1)$ elements $(h, g, g^a, g^{a^2}, \ldots, g^{a^{n+2}}, \ldots, g^{a^{2n}}) \in G^{2n+1}$ and $R \in G_T$ for an unknown random $\alpha \in \mathbb{Z}_N$, determine whether $R = e(g, h)\alpha^{n+1}$ or a random element from $G_T$.

**Definition 4.** (The (decisional) n-BDHE assumption) We say that the (decisional) n-BDHE assumption holds if no probabilistic and polynomial-time algorithm has advantage at least $\epsilon$ in solving the (decisional) n-BDHE problem.

3.2 Boneh-Goh-Nissim Cryptosystem

The Boneh-Goh-Nissim cryptosystem (BGN) includes three algorithms: key generation, encryption, and decryption. The details are described as follows.

- **Key generation:** Given a security parameter $\kappa$, run $Gen(\kappa)$ to get a tuple $(p, q, G, G_T, e)$ as described in Section 3.1 and set $N = pq$. Randomly choose two generators $g, x \in G$ and set $y = x^3$. The private key is $p$ and the corresponding public key is $pk = (N, G, G_T, e, g, y)$.
3.3 B+ Tree

The B+ tree of order $f$ is a very efficient, dynamic and balanced search tree that satisfies the following properties:

- The root node has at most $f$ children and at least two children if it is not a leaf node.
- Each non-leaf node with $n_c$ children contains $n_c - 1$ keywords: $(P_0, \delta_1, P_1, \delta_2, P_2, \ldots, \delta_{n_c-1}, P_{n_c-1})$, where
  - $\delta_k$, $k = 1, 2, \ldots, n_c - 1$, is a keyword with $\delta_{k-1} < \delta_k$.
  - $P_k$ is a pointer that points to the root of the subtree.
  - All the keywords pointed by $P_{k-1}$ are smaller than $\delta_k$, but greater than or equal to $\delta_{k-1}$.
  - The number of children is satisfied $\left\lfloor \frac{f}{2} \right\rfloor \leq n_c \leq f$.
- Each leaf node (unless it is a root) must contain $n_c - 1$ keyword and pointer pairs: $(\delta_1, P_1, \ldots, \delta_{n_c-1}, P_{n_c-1})$, where
  - $\left\lfloor \frac{f}{2} \right\rfloor - 1 \leq n_c - 1 \leq f - 1$.
  - All data is stored in leaf nodes, and the pointer $P_k$, $k = 1, \ldots, n_c - 1$, points to the data that contains the keyword $\delta_k$.
  - Each leaf node has a link to its adjacent sibling, forming the ordered linked list.
- All leaves appear in the same level.

An example of a B+ tree is illustrated in Fig. 2. Since all data are stored in leaf nodes, that is all keywords queries have the same path length (from the root to the leaf), the efficiency of search is more stable compared to other trees, e.g., the binary search tree [25] or B-tree [26]. As introduced in [15], the time complexity of the search operation in a B+ tree is $O(\log_f M)$, where $M$ is the number of stored data. Therefore, a B+ tree can be used even when the data structure is too big to fit into main memory.

![Fig. 2: A simple B+ tree of order 4 example linking keywords 1 – 7 to data values d1 – d7.](image-url)

### 4 The Proposed Scheme

In this section, we present our scheme, which includes three phases: system setup, data upload, and data download.

#### 4.1 System Setup

In this phase, the trusted KDS generates private keys for users, a secret for the CSP and the corresponding system parameters. Specifically, the KDS first runs the composite bilinear parameter generator $Gen(\kappa_0)$ to output a tuple $(N = pq, G, G_T, e)$. Then, the KDS generates system parameters and private keys as follows.

- Randomly choose two generators $g, x \in \mathbb{G}$ and two numbers $\alpha, \gamma \in \mathbb{Z}_N$, and then compute $y = x^\alpha, \nu = y^\gamma$ and $g_i = g^\alpha$ for $i = 1, 2, \ldots, n, n + 2, \ldots, 2n$.
- For all users in $D_i$, compute the private key $d_i$ as $d_i = g_i^\gamma$, where $i = 1, 2, \ldots, n$. Note that $n$ is the total number of domains in system and $i$ is the identifier of $D_i$.
- Choose three cryptographic hash functions: $h_1 : \{0, 1\}^* \rightarrow \{0, 1\}^{\kappa_1}, h_2 : \{0, 1\}^* \rightarrow \{0, 1\}^{\kappa_0-1}$ and $h_3 : \mathbb{G} \rightarrow \{0, 1\}^{\kappa_1}$, where $\kappa_1$ is the bit length of the convergent key.

Finally, the KDS sends $d_i$ to all users in $D_i$ and $p$ to the CSP by secure channels, and publishes system parameters $pp = (N, G, G_T, e, h_1, h_2, h_3, y, g, g_1, \ldots, g_{n+2}, \ldots, g_{2n}, \nu)$.

In addition, based on the published system parameters, each agent $A_i$ randomly chooses $a_i \in \mathbb{Z}_N$ as the private key, and then computes the corresponding public key $g^{a_i}$. Finally, $A_i$ sends $g^{a_i}$ to all users who belong to the domain $D_i$.

Note that in the practical scenario, it is important to support the dynamic addition of domains or users, especially for adding users, e.g., hiring new employees. The proposed scheme can easily support the addition of users to the existing domains. Specifically, suppose that a user $U^*$ is added to the domain $D_i$, we can introduce a simple identity verification protocol that allows $U^*$ to verify the legitimacy to the KDS. If the identity verification is passed, the KDS sends the corresponding private key $d_i$ to $U^*$ through the secure channel. After that, $U^*$ can upload data in the same way as the users previously added to $D_i$.

For the addition of new domains, it seems impossible to increase $n$ (i.e., the number of domains) after the scheme is once instantiated. However, similar to the concept of initializing arrays, we can initialize a relatively large $n$ to reserve enough space to support the dynamic addition of domains to some extent. For example, if the number of domains is 10 in the current situation, then we can set $n$ to 20. The reserved portion can be used for subsequent domain additions.

#### 4.2 Data Upload

The data upload phase mainly includes four parts: tag generation, intra-deduplication, inter-deduplication and data encryption key recovery. For each user $U$ in $D_i$, where $i = 1, 2, \ldots, n$, when $U$ wants to upload the data $m$, $U$ first generates an intra-tag for data deduplication. Then, the agent $A_i$ performs the intra-deduplication to check the duplicate in the same domain $D_i$. If the duplicate does not exist, then the CSP needs to further conduct the inter-deduplication among different domains. Finally, if the duplicate is found, then $U$ recovers the convergent key generated by the first uploader. Otherwise, $U$ encrypts $m$ and uploads the corresponding ciphertexts. The details are described as follows.
4.2.1 Tag generation
When a user \( U \) from \( D_i \) wants to upload data \( m \), \( U \) chooses a random number \( r_m \in \mathbb{Z}_N \), and generates a random intra-tag \( \tau_m \) with the private key \( d_i \) and \( A_i \)’s public key \( g^h \) as
\[
\tau_m = \left( d_i h^2(m) g^{a_i r_m}, g^{r_m} \right) = \left( g^{a_i \alpha \cdot h_2(m) + a_i r_m}, g^{r_m} \right). \tag{1}
\]
Then, \( U \) sends a message “upload\(|L_m, \tau_m\)” to \( A_i \). Note that \( L_m \) is the length of \( m \), which acts as the search keyword of the deduplication decision tree (DDT) in the inter-deduplication.

4.2.2 Intra-deduplication
Upon receiving the message “upload\(|L_m, \tau_m\)” from \( A_i \), \( U \) performs the intra-deduplication as follows.

1) Based on the private key \( a_i \), compute
\[
d_i h^2(m) \quad (g^{r_m})^{a_i} = d_i h^2(m) = g^{a_i \alpha \cdot h_2(m)}. \tag{2}
\]
Then, the hash of \( d_i h^2(m) \) as \( T_m = h_3 \left( d_i h^2(m) \right) \).

2) Check whether a duplicated copy of \( m \) exists by comparing \( T_m \) to previously stored hash values from \( D_i \).
   - If the same hash value has already been stored, e.g., \( (T_m', B_m') \), then \( A_i \) returns “duplication||\(|B_m'||\)” to \( U \). Note that \( B_m' \) is the ciphertext used to encapsulate some information of the convergent keyword, which will be introduced in Section 4.2.4.
   - Otherwise, \( A_i \) uses the value \( d_i h^2(m) \) to generate a random inter-tag \( \hat{\tau}_m \) based on the BGN encryption. \( A_i \) randomly chooses \( r \in \mathbb{Z}_N \), and computes
\[
\hat{\tau}_m = d_i h^2(m) \cdot y^r \in \mathbb{G}. \tag{3}
\]
Then, \( A_i \) stores \( T_m \) in the hash table and sends the message “upload\(|(i, L_m, \hat{\tau}_m)|\)” to the CSP for the inter-deduplication, where \( i \) is the identifier of \( D_i \).

At this point, the intra-deduplication part has only checked the duplicate among the outsourced data from the same domain, i.e., \( D_i \). Thus, if the duplicate is not found in the intra-deduplication, it needs to further perform the inter-deduplication to check whether the same data has been uploaded by users from different domains.

4.2.3 Inter-deduplication
After receiving the message “upload\(|(i, L_m, \hat{\tau}_m)|\)” from \( D_i \), the CSP performs the inter-deduplication to further eliminate the redundancy of data. Note that in the inter-deduplication, \( A_i \) judges whether the duplicate exists by comparing hash values. Thus, the search complexity is very efficient, i.e., \( O(1) \). However, in the inter-deduplication, since inter-tags are random elements in \( \mathbb{G} \) generated by BGN encryption, the same data will correspond to different inter-tags. Thus, the CSP cannot compare the hash values of inter-tags to check the duplicate. Nevertheless, if the one by one search method is adopted, the time complexity of duplicate search increases linearly with the number of encrypted data stored in the CSP, which will lead to huge search costs, especially for big data. Accordingly, we construct a deduplication search tree (DDT) based on the B+ tree for efficiently searching duplicates. The details are shown as follows.

**Deduplication decision tree (DDT):** According to the introduction of the B+ tree in Section 3.3, we construct a DDT of order \( f \), as shown in Fig. 3. In the constructed DDT, the keyword used for dividing subtrees is the length of the data \( L_m \), and each leaf node has \( n_c - 1 \), where \( \left( \frac{L}{2} \right) \leq n_c \leq f \), pointers to point the stored data that contains the keyword \( L_m \), i.e., \((i, L_m, \hat{\tau}_m, B_m, C_m)\). In the inter-deduplication, the CSP leverages Algorithm 1 to search a duplicate of \( L_m \).

**Algorithm 1 Search algorithm in the deduplication decision tree**

**Function:** \( \text{Search}(L_m, \text{node}) \)

1: The search function \( \text{Search}(L_m, \text{node}) \) is started from the root node, i.e., \( \text{node} = \text{root} \), and it proceeds to a leaf node as follows:
2: if \( \text{node} \) is a leaf then
3: \( \text{return} \) node
4: else
5: \( \text{case 1: } L_m < \delta_1 \) then
6: \( \text{return} \) \( \text{Search}(L_m, P_0) \)
7: \( \text{case 2: } \delta_k < L_m < \delta_{k+1} \) then
8: \( \text{return} \) \( \text{Search}(L_m, P_k) \)
9: \( \text{case 3: } \delta_{n_c-1} \leq L_m \) then
10: \( \text{return} \) \( \text{Search}(L_m, P_{n_c-1}) \)
11: end if
12: Note that \( 1 \leq k < n_c - 1 \), the keyword \( \delta_k \) is the value of the data length \( L_m \). Each non-leaf node contains \( n_c - 1 \) keywords and \( n_c \) pointers: \((P_0, \delta_1, P_1, \delta_2, P_2, \ldots, \delta_{n_c-1}, P_{n_c-1})\).

**Inter-deduplication:** The CSP starts checking the duplicate from the root node by comparing the data length \( L_m \) as shown in Algorithm 1. If the same value \( L_m^* \) is found, then for the corresponding stored data \((j, \hat{\tau}_m^*, B_m^*, C_m^*)\), the CSP leverages Algorithm 2 to check whether the duplicate exists or not. If the data \( m \) is a duplicate, then the CSP sends “duplication||\(|\text{link}_{m^*}|\|B_m^*\)” to \( A_i \), where \( \text{link}_{m^*} \) is the logical link to the data \( C_m^* \). Otherwise, the CSP sends “data upload” to \( A_i \). The details of the inter-deduplication are described in Algorithm 2, wherein lines 5 to 7, the CSP needs to check whether \( i = j \) holds. The reason is that if \( i = j \), it means that the received data \((i, L_m, \hat{\tau}_m)\) and stored data \((j, L_m^*, \hat{\tau}_m^*, B_m^*, C_m^*)\) come from the same domain \( D_i \). Actually, the inter-deduplication part (see Section 4.2.2) has already checked the duplicate in the same domain \( D_i \). Only when the duplicate is not found, i.e., \( m \neq m^* \), the data \((i, L_m, \hat{\tau}_m)\) will be sent to the CSP for inter-deduplication. Hence, when \( i = j \), we can judge that the data \( m \) and \( m^* \) are different without the further verification. Fig. 3 shows an example of searching the duplicate.

**Corollary 1.** (Correctness of inter-deduplication) Suppose two inter-tags \( \hat{\tau}_m \) and \( \hat{\tau}_m^* \) are from different domains \( D_i \) and \( D_j \), where \( i, j \in \{1, \ldots, n\} \) and \( i \neq j \), respectively. The equation
\[
eq \hat{\tau}_m^* \end{equation}
holds, if and only if \( m_k = m_k^* \).

**Proof.** Since
\[
\hat{\tau}_m = d_i h^2(m_k), \quad y^{r_k} = g^{a_i \alpha \cdot h_2(m_k)}, \quad y^{r_k}^* = d_j h^2(m_k^*), \quad y^{r_k^*} = g^{a_j \alpha \cdot h_2(m_k^*)}, \quad y^{r_k^*}
\]


Theory and Algorithms

Algorithm 2 Inter-deduplication algorithm

1. For the received data \((i, L_m, \tilde{r}_m)\), the CSP calls the function Search\((L_m, \text{node})\) in the DDT to search whether the value \(L_m\) has already been stored.
2. if \(\text{the same value is not found}\) then
   3. \text{return} \(\text{“data upload”}\)
   4. else
5. \(\text{the same value} L_{m^*} \text{ is found}, \text{e.g.}, (j, \tilde{r}_{m^*}, B_{m^*}, C_{m^*})\), and then check whether \(i = j\) holds.
6. if \(i = j\) then
7. \text{return} \(\text{“data upload”}\)
8. else
9. verify whether the following equation holds

\[
\epsilon(\tilde{r}_m, g_j)^p = \epsilon(\tilde{r}_{m^*}, g_i)^p \tag{4}
\]

10. if Eq. (4) holds then
11. \text{return} \(\text{“duplication}||L_{m^*}\|B_{m^*}”\)
12. else
13. \text{return} \(\text{“data upload”}\)
14. end if
15. end if

According to Corollary 1, Eq. (4) holds, if and only if \(m = m^*\). That is, the duplicate can be found by verifying Eq. (4).

\[
\epsilon(\tilde{r}_m, g_j)^p = \epsilon(\tilde{r}_{m^*}, g_i)^p
\]

where \(a\) follows from the condition \(\epsilon(x, g)^N = 1\) as the order of the group \(\mathbb{G}_T\) is \(N\).

Based on the above analyses, we can obtain that if and only if \(m_k = m\), i.e., \(h_2(m_k) = h_2(m)\), then

\[
\epsilon(g, g)^{\alpha + 1 + \gamma p h_2(m_k)} = \epsilon(g, g)^{\alpha + 1 + \gamma p h_2(m)}
\]

\[
\Leftrightarrow \epsilon(\tilde{r}_m, g_j)^p = \epsilon(\tilde{r}_{m^*}, g_i)^p
\]

Note that \(h_2 : \{0, 1\}^* \rightarrow \{0, 1\}^{k-1}\) is a cryptographic hash function, and the hash value satisfies \(h_2(m_k) < q\) for the arbitrary data \(m_k\).

\[\square\]

4.2.4 Data encryption / key recovery

Upon receiving the message “duplication||link_{m^*}||B_{m^*}”, \(A_i\) forwards “duplication||B_{m^*}” to the user \(U\) and stores \((B_{m^*}, \text{link}_{m^*})\) together with \(T_m\), i.e., \((T_m, B_{m^*}, \text{link}_{m^*})\), where \(m = m^*\). Otherwise, \(A_i\) directly forwards the message “data upload” to \(U\). After receiving the feedback from \(A_i\), if the message is “data upload”, \(U\) performs data encryption operations. If the received message is “duplication||B_{m^*}”, \(U\) conducts key recovery operations. The details are described as follows.

Data encryption: If the message is “data upload”, \(U\) encrypts the data \(m\) before outsourcing as follows.

- Randomly choose \(\beta_m \in \mathbb{Z}_N\), set \(K_m = e(g_{n+1}, g)^{\beta_m}\), and generate the convergent key \(cK_m\) as

\[
\begin{align*}
\text{ck}_m &= h_1(\text{K}_m||m) = h_1(e(g_{n+1}, g)^{\beta_m}||m).
\end{align*}
\]

Note that the value \(e(g_{n+1}, g)\) can be computed as \(e(g_i, g_{n+1}-i)\).

- Generate the ciphertext of \(m\) as

\[
\begin{align*}
B_m &= (g^{\beta_m \tau}, \prod_{k \in \mathbb{Z}} g^{n+1-k})^{\beta_m}, \quad C_m = \text{SKE}_\text{ck}_m(m),
\end{align*}
\]

where the set \(\mathbb{T} = \{1, 2, \ldots, n\}\) is comprised of the identifiers of \(n\) domains and \(\text{SKE}_\text{ck}_m(\cdot)\) represents a fast symmetric encryption algorithm, like AES. Finally, the ciphertext tuple of the data \(m\) is \((B_m, C_m)\).

Note that the ciphertext \(B_m\) is used to encapsulate the random value \(K_m\). The idea of computing \(B_m\) comes...
from the broadcast encryption scheme [27], which has an advantage that the number of ciphertexts is constant for any set of receivers. Therefore, we can combine the convergent encryption with this broadcast encryption scheme to guarantee that the outsourced encrypted data can be correctly decrypted by users with ownership while improving the efficiency of computation, communication, and storage. The details about the performance will be analyzed in Section 6.

After data encryption, U sends \((B_m, C_m)\) to \(A_i\). Upon receiving \((B_m, C_m)\), \(A_i\) forwards it to the CSP and stores \((T_m, B_m)\). Finally, the CSP stores \((i, L_m, \tau_m, B_m, C_m)\) in the appropriate location of the DDT by leveraging Algorithm 1, and sends the link message \(m\) to \(A_i\). That is, \(A_i\) finally stores \((T_m, B_m, \text{link}_m)\).

**Key recovery:** If the message is “duplication \(B_m\)”, then \(U\) recovers the convergent key \(ck_m = h_1(e(g_{n+1}, g)^{\mu m} \parallel m)\) with the private key \(d\) and the data \(m\) as follows.

- **Let** \(B_m = (B_0, B_1)\), compute
  \[ e(g_{n+1}, g)^{\mu m} = e(d_i \cdot \prod_{k \in Z} g_{n+1-k}, B_0) \]  \hspace{0.5cm} (7)

- Then, \(U\) can recover \(ck_m\) with the data \(m\) as: \(ck_m = h_1(e(g_{n+1}, g)^{\mu m} \parallel m)\). Note that in this case, the data \(m\) is the duplicate of the data \(m\), i.e., \(m = m^*\).

The correctness of Eq. (7): Based on Formula (6), the ciphertext \(B_m\) can be computed as

\[ B_m = (B_0, B_1) = (g^{\mu m}, (\nu \cdot \prod_{k \in I} g_{n+1-k})^{\mu m^*}). \]

We can obtain

\[ e(g_i, B_1) = e(g_i, (\nu \cdot \prod_{k \in I} g_{n+1-k})^{\mu m^*}) \]
\[ = e(g_i, g_{n+1-i})^{\mu m^*} \cdot e(g_i, \nu \cdot \prod_{k \in I} g_{n+1-k})^{\mu m^*} \]
\[ = e(g^\alpha, g^\alpha n_{n+1-i})^{\mu m^*} \cdot e(g, \nu^\alpha \cdot \prod_{k \in I} g_{n+1-k})^{\mu m^*} \]
\[ = e(g, g)^{\alpha n_{n+1-i} \cdot \mu m^*} \cdot e(g, \nu^\alpha \cdot \prod_{k \in I} g_{n+1-k+1})^{\mu m^*} \]

where \(g_i^{\alpha n_{n+1-i}} = (g^\alpha n_{n+1-i})^\alpha = g_{n+1-i} \).

\[ e(d_i \cdot \prod_{k \in I} g_{n+1-k+i}, B_0) = e(g_i, \prod_{k \in I} g_{n+1-k+i}, g^{\mu m}) \]
\[ = e(\nu^\alpha \cdot \prod_{k \in I} g_{n+1-k+i}, g)^{\mu m^*} \]

where \(g_i^\alpha = g^\alpha \cdot g^\alpha = (g^\alpha)^{\mu^\alpha} = \nu^\alpha\).

Accordingly, we can obtain

\[ e(g_i, B_1) = e(g_i, g)^{\alpha n_{n+1-i} \cdot \mu m^*} = e(g_i, g)^{\mu m^*}. \]

Finally, \(U\) deletes the data \(m\) and just stores the information \((T_m, ck_m, \text{link}_m)\), where \(T_m = h_3(d_i^{\mu m^*})\), \(\text{link}_m\) is the label of the data \(m\), e.g., the name or feature used for identifying the data \(m\). The reason for using \(\text{link}_m\) is to make it easy for users to identify each data. Note that if \(m\) is the duplicate, then \(ck_m = ck_m = h_1(e(g_{n+1}, g)^{\mu m} \parallel m)\), where \(e(g_{n+1}, g)^{\mu m^*}\) is generated by the first uploader. Otherwise, \(ck_m = h_1(e(g_{n+1}, g)^{\mu m} \parallel m)\) is generated by himself.

### 4.3 Data Download

After a period of time, when the user \(U\) from \(D_i\) wants to download an outsourced data \(m\), \(U\) uses the corresponding label \(\text{link}_m\) to find the stored \(T_m\), and then sends a request “download \(T_m\)” to \(A_i\). After receiving the request “download \(T_m\)”, \(A_i\) finds the same hash value and get the corresponding link \(\text{link}_m\). Then, \(A_i\) returns \(\text{link}_m\) to \(U\). After that, \(U\) can directly download the ciphertext \(C_m\) from the CSP based on the \(\text{link}_m\).

Finally, \(U\) decrypts \(C_m\) with the stored convergent key \(ck_m\) and verifies data integrity. The details are introduced as follows.

- \(U\) recovers \(m\) by decrypting \(C_m\) with \(ck_m\).
- Then, with the recovered \(m\), \(U\) computes \(T_m = h_3(d_i^{\nu m})\), and verifies the integrity by checking whether \(T_m = T_m\) holds. If it does not hold, it means that \(m\) has been corrupted, i.e., \(m \neq m\).

Note that in our scheme, if a user from \(D_i\) has previously tried to upload the data \(m\). After the data deduplication, no matter whether \(m\) is successfully uploaded, \(A_i\) has a record of this data, i.e., \((T_m, B_m, \text{link}_m)\). Conversely, if \(A_i\) does not store the corresponding record, then it means that no user in \(D_i\) has ever tried to upload the data \(m\), that is all users in \(D_i\) do not have the access right to this data. Therefore, users only need to interact with \(A_i\) to obtain the corresponding logical link, which can reduce the download time to a great extent compared to the interaction with the CSP.

### 5 Security Analysis

In this section, we analyze the security properties of our scheme. In particular, following the design goals illustrated in Section 2.3, our analysis will focus on how our scheme can achieve data confidentiality and data integrity while resisting brute-force attacks.

#### 5.1 Data Confidentiality

Data confidentiality of our scheme includes two aspects: (1) The semantic security of encrypted data and tags; (2) The preservation of the message equality information. The details are analyzed as follows.

##### 5.1.1 Semantic security of encrypted data and tags

In our scheme, any adversary even corrupting the CSP and \(A_i\) or unauthorized users cannot feasibly extract any information about a plaintext from its ciphertext or tag.

First, we analyze that \(A_i\) and the CSP cannot obtain the content from the stored or received data. Specifically, \(A_i\) can receive the data \((L_m, \tau_m, B_m, C_m)\) from the user \(U\) in \(D_i\). With the private key \(a_i\), \(A_i\) can obtain \(g^\alpha h_2(m)\) from the intra-tag \(\tau_m\) (see Eq. (2)). If \(A_i\) wants to obtain the data \(m\) from \(g^\alpha h_2(m)\), \(A_i\) first needs to overcome the discrete logarithm problem (DLP) to obtain \(\alpha^\gamma h_2(m)\), and then deals with the integer factorization to obtain \(h_2(m)\). At last, \(A_i\) has to compute the one-way hash function
to get $m$. However, the DLP, integer factorization and one-way hash function have been proved to be computationally infeasible difficult problems [28]. Hence, it is infeasible to get $m$ from the intra-tag $\tau_m$. If $A_i$ wants to get $m$ from $(B_m,C_m)$, $A_i$ tries to get the random element $K_m = e(g_{n+1}, g)^{d_m}$, which is the crux of the convergent key $ch_m = h_1(K_m \parallel m)$. However, based on the $n$-BDHE hard problem (see Definition 2), $A_i$ cannot obtain $K_m$ from the parameters $(g^{d_m}, g_1, \ldots, g_n, g_{n+2}, \ldots, g_{2n})$. Besides, based on the decisional $n$-BDHE problem (see Definition 3), without the private key $d_i$, $A_i$ cannot recover $K_m$ from $B_m$ (see [27] for details). Without knowing the random $K_m$, the convergent ciphertext $C_m$ is a random ciphertext generated by the symmetric encryption algorithm, which satisfies the semantic security [4], [29]. Note that the value $L_m$ denotes the size of the data $m$, it is a feature that every data possesses. In general, this value would not leak any information about the data content. Therefore, $A_i$ cannot obtain any information about the data $m$ from the obtained data $(L_m, \tau_m, B_m, C_m)$.

The CSP stores $(i, L_m, \tau_m, B_m, C_m)$ received from $A_i$. Similarly, without the private key $d_i$, the CSP cannot obtain the data $m$ from the ciphertext tuple $(B_m, C_m)$. For the inter-tag $\tau_m = g^{\alpha_m h_2(m)}$ generated by the BGN encryption, the CSP possesses the secret $\tau$ and can compute $(\tau_m)^p = (g^p)^{\alpha_m h_2(m)}$. Recall in Section 3.2, when the plaintext space is small, say $\alpha = 1$, $h_2$ becomes a hard problem. Thus, the CSP cannot obtain any private information in the cross-domain and other entities cannot know $h_2$ or the private parameters $\alpha$ and $\gamma$.

Then, we analyze that users lacking ownership cannot read the data content from the encrypted data. For any user $U$ in $D_1$, if $U$ tries to obtain the data that does not own by himself, $U$ can choose a random number $H$ such that the bit length of $H$ is $\kappa_0 - 1$. Then, $U$ generates an intra-tag $T_H = (d_i^H g^{a_i H}, g^r)$ with the private key $d_i$. After that, $U$ interacts with $A_i$ to execute the data upload phase. If an identical hash value $T_m = h_3(d_2^{\tau_2(m)})$ happens to be stored, i.e., $H = h_2(\rho^*)$, then $U$ can retrieve the corresponding ciphertext $B_{m*}$. Accordingly, $U$ can recover the value $K_{m*} = e(g_{n+1}, g)^{d_{m*}}$ from $B_{m*}$ by computing Eq. (7). However, $U$ does not possess the data $m^*$, and thus $U$ cannot generate the convergent key $ch_{m*} = h_1(K_{m*} \parallel m^*)$. In fact, the probability that a randomly selected $H$ equals to $h_2(m^*)$ is very small, i.e., $P = \frac{1}{2^{\kappa_0 - 1}}$. Thus, when the security parameter $\kappa_0$ is large enough, it is almost impossible to obtain $K_{m*}$ through such attempts.

5.1.2 Preservation of message equality information

We prove that our scheme can protect the message equality information from disclosure to some extent. Actually, in order to achieve data deduplication, the message equality information has to be leaked. Fortunately, our scheme can minimize such disclosure. Specifically, during the intra-deduplication, before obtaining the hash value $T_m$ to compare, Eq. (2) has to be performed, i.e., $d_i^{\tau_2(m)} g^{a_i \tau_2(m) \parallel \rho^*} = d_i^{\tau_2(m)}$. Since only $A_i$ possesses the private key $a_i$, based on the CDH problem (see Definition 1), only it can compute Eq. (2). In other words, only $A_i$ knows the message equality information in the domain $D_i$. In the inter-deduplication, to verify whether two inter-tags from different domains correspond to the same data, it has to verify whether Eq. (5) holds, i.e., $e(\tau_m, g_j)^p = e(\tau_m, g_j)^p$. Since only the CSP possesses the secret $p$, only the CSP can compute Eq. (5) to complete the verification. That is, only the CSP knows the message equality information in the cross-domain and other entities cannot know whether the stored ciphertext and a given tag correspond to an identical plaintext. Therefore, compared to most related works where any entity can perform the duplicate verification to obtain the message equality information, our scheme can reduce the disclosure of such information as much as possible.

5.2 Data Integrity

After obtaining the data $m'$, it is very necessary for $U$ to verify data integrity to ensure the stored data $m'$ is not altered. The reason is that deduplication techniques only keep one copy. Without the assurance of data integrity, once the outsourced data is altered, $U$ cannot obtain the correct original data and even cannot be aware of such change.

Our scheme allows users to easily verify data integrity. Specifically, $U$ generates the value $T_m' = h_3(d_2^{\tau_2(m')})$. Recall that after the data upload phase, $U$ stores the hash value $T_m = h_3(d_2^{\tau_2(m)})$. Then $U$ checks whether $T_m' = T_m$ holds. As we consider hash functions $h_2$ and $h_3$ as random oracles, if $T_m' \neq T_m$, then $m' \neq m$, which implies that the downloaded data $m'$ is corrupted.

5.3 Brute-Force Attacks Resistance

In this section, we analyze that our scheme can prevent the CSP, $A_i$ or the malicious user (corrupted by the adversary) from obtaining the content of the targeted ciphertext by launching brute-force attacks.

5.3.1 Security against offline brute-force attacks

First, we consider an offline brute-force attack launched by the CSP or $A_i$ on the accessible information. Suppose the CSP knows the background knowledge of the plaintext space $\mathcal{M}$, and wishes to know which data corresponds to the specific ciphertext or tag. That is, for a stored data $(i, \tau_m, B_m, C_m)$, where $\tau_m = d_2^{\tau_2(m)} g^r$, $B_m = (g^m, (u \prod_{i \in \mathcal{I}} g_{n+1}^{-1})^{\beta_m})$, $C_m = \text{SKE}_{k_{c_m}}(m)$, the CSP wishes to determine which data $m_i \in \mathcal{M}$ generates them by launching offline brute-force attacks.

More specifically, with the secret key $p$, the CSP computes $d_i^{\tau_2(m')}$ for each data $m_i \in \mathcal{M}$. The CSP first computes the hash value $h_2(m_i)$, and then wishes to generate $d_2^{\tau_2(m_i)p}$ to check whether $d_i^{\tau_2(m_i)p} = d_i^{h_2(m_i)}$. If this holds, then it implies that $h_2(m_i) = h_2(m_i)$, i.e., $m_i = m_i$. Unfortunately, the CSP cannot generate the valid value $d_2^{\tau_2(m_i)p}$ without the private key $d_i$. Thus, the CSP cannot obtain the content from the inter-tag by an offline brute-force attack. Moreover, without the private key $d_i$, the CSP cannot obtain the value $K_m = e(g_{n+1}, g)^{d_m}$ from $B_m$ or public parameters due to the (decisional) $n$-BDHE hard problem. Accordingly, the CSP cannot generate the valid convergent key $ch_m = h_1(K_m \parallel m)$ without $K_m$. That is, the CSP cannot generate a valid ciphertext $C_m$, nor decrypt $C_m$ to judge whether $m_i = m_i$ or not. Therefore, the CSP cannot determine which plaintext corresponds to the specific encrypted data and tag by launching offline brute-force attacks.

In our threat model, $A_i$ also wants to obtain the content of the stored data by launching offline brute-force attacks. Specifically, for the obtained data $(\tau_m, B_m, C_m)$, where $\tau_m = d_i^{h_2(m)} g^{a_i \tau_m}$, $A_i$ can use the private key $a_i$ to obtain $d_i^{\tau_2(m)}$ from the intra-tag $\tau_m$. Similarly, for each data $m_i \in \mathcal{M}$,
A computes \( h_2(m) \) and tries to generate \( d_i^{h_2(m)} \) to check whether \( d_i^{h_2(m)} = d_i^{h_2(m)} \) holds. However, it cannot generate a valid \( d_i^{h_2(m)} \) without \( d_i \). Similar to the CSP, \( A \) cannot obtain useful information from the encrypted data \((B_m, C_m)\). Therefore, \( A \) also cannot guess the content of the targeted ciphertext or tag by launching offline brute-force attacks.

### 5.3.2 Security against online brute-force attacks

In addition to the CSP and \( A \), a malicious user (corrupted by the adversary) from the domain \( D_i \) may launch an online brute-force attack by repeatedly executing the data upload procedure. For each data \( m_t \in M \), he/she generates the intra-tag \( \tau_m \), and tries to upload \( m_t \) to observe whether uploading of \( m_t \) has occurred. The online brute-force attack repeats this procedure until the duplicate exists. That is, the malicious user can know the content corresponding to the targeted ciphertext.

Although such an attack cannot be completely prevented because the user has the private key, the actual effect of the attack can be minimized. Similar to existing works associated with brute-force attacks [5], [8], [11], we adopt the rate-limiting strategy to mitigate such attack. Specifically, we use the bounded rate-limiting approach of DupLESS [5]. In this approach, each \( A \) sets the total number of data upload requests a user can make during a fixed time interval, e.g., \( A \) can set the maximum number of times to perform Eq. (2). By doing so, we can greatly reduce the capability of the malicious user to execute this online brute-force attack.

### 6 PERFORMANCE EVALUATION

We evaluate the performance of our scheme in terms of computational, communication and storage overheads. Moreover, we give a comparison with Shin et al’s scheme [8] and Jiang et al’s scheme [30]. Since these three schemes use a symmetric encryption algorithm to generate the data ciphertext, we ignore related overheads of the same part in the comparison.

#### 6.1 Theoretical analysis

In this section, we discuss the theoretical analysis and give a comparison of three schemes. Similarly to [8] and [30], we ignore the costs of the KDS since it does not participate in data upload and download phases. Besides, compared to the exponentiation and pairing operations, the computational cost of a hash operation is very fast, which can be ignored. In what follows, we describe computational costs and communication overhead of uploading and downloading the data \( m \), and also show the related storage costs.

##### 6.1.1 Computational Cost

For the sake of simplicity, we use \( t_m, t_{m_t}, t_c, t_{el} \) and \( t_p \) to represent the computational cost of a multiplication in \( G \), a multiplication in \( G_T \), an exponentiation in \( G \), an exponentiation in \( G_T \) and a pairing, respectively.

1. **Computational cost of our scheme.** In the phase of data upload, an intra-tag \( \tau_m \) is first generated, which requires \( 3t_c + t_m \). Then, \( A \) computes Eq. (2) and \( T_m \) to check the duplicate, which costs \( t_c + t_m \). If the duplicate exists, then \( A \) returns “duplication \( B_m \)” to the user. Otherwise, \( A \) computes the inter-tag \( \tau_m \), which costs \( t_c + t_m \). After that, the CSP receives \((i, L_m, \tau_m)\) and performs the inter-deduplication. Based on Algorithm 2, the CSP first searches whether the value \( L_m \) is recorded. The search complexity in DDT is \( O(\log |S_{all}|) \), where \( |S_{all}| \) denotes the number of stored data in the CSP. If the same value is found, the CSP needs to verify whether Eq. (4) holds, which costs \( 2t_p \). Note that \( \epsilon(t_m, g_j)^p = \epsilon(t_m, g_j^p) \). Once the system is set up, the value \( g_j^p, j = 1, ..., n, \) can be computed offline by the CSP and will remain unchanged. Thus, the cost of \( g_j^p \) can be ignored. After finishing data deduplication, if the duplicate is not found, the user encrypts \( m \) as \((B_m, C_m)\). In addition to the cost of \( C_m \), the additional costs are \( 2t_p + t_d \). Note that, \( B_m \) is computed as \( B_m = (g_m, \nu \cdot \prod_{k \in T} g_{m_k + n + 1 - k}) \). Similarly, once the system is set up by the KDS, the value \( \nu \cdot \prod_{k \in T} g_{m_k + n + 1 - k} \) is a constant. Accordingly, \( (n - 1)t_e \) can be ignored. However, if the duplicate is found, the user needs to recover the convergent key \( c_k m^* \). The crux is to obtain the value \( \epsilon(g_{m+1}, g)^{2m^*} \) by computing Eq. (7). Likewise, for each user from \( D_i \), \( d_i \cdot \prod_{k \in T} g_{m_k + n + 1 - k} + 1 \) can be considered as a constant when the system is set up. Therefore, the corresponding costs are \( t_m + 2t_p \).

In the phase of data download, it contains the decryption and data verification. Since we ignore the cost of the symmetric encryption algorithm, we only discuss data verification. With the decrypted data \( m' \), the user computes \( T_m' = h_2(d_i^{h_2(m')} \), and then verifies the integrity by checking whether \( T_m' = T_m \) holds. Thus, the cost of data download is \( t_c \).

2. **Comparison of computational cost.** In order to make a comparison, we list the computational costs of three schemes in Table 1. Note that, \( |S_{all}| \) and \( |S_p| \) denote the number of encrypted data stored in the CSP and from the \( D_i \), respectively. \( l \) is the bit length of short hash used in [8] and usually around 5 ~ 20 bits.

##### 6.1.2 Communication Overhead

In order to facilitate the analysis, we use \(|G|\) and \(|G_T|\) to denote the bit length of an element in \( G \) and \( G_T \), respectively. \(|L|, |link|\) and \( |i| \) denote the bit length of the data length \( L_m \), the data link \( link_m \) and the domain identifier \( i \), respectively.

- **Communication overhead of our scheme.** When a user \( U \) in \( D_i \) wants to upload data \( m \), \( U \) first sends “upload \((L_m, \tau_m)\)” to \( A_i \), which costs \(|L| + 2|G| \) bits. If the duplicate is found, then \( A_i \) returns “duplication \( B_m \)” with \( 2|G| \) bits in length to \( U \). If the duplicate is not found, then \( A_i \) sends “upload \((i, L_m, \tau_m)\)” with \(|i| + |L| + |G| \) bits in length to the CSP for the further inter-deduplication. Then the CSP returns “duplication \( \text{link}_m \circ B_m \)” with \(|link| + 2|G| \) bits in length to \( A_i \) when the duplicate is found. Otherwise, the CSP returns “upload” to \( A_i \). After the inter-deduplication, \( A_i \) either returns “duplication \( B_m \)” with \( 2|G| \) bits in length or directly forwards “upload” to \( U \). If the received message is “upload”, then \( U \) sends the encrypted data \((B_m, C_m)\) to \( A_i \). Except for the symmetric ciphertext \( C_m \), the additional overhead is \(|G| \) bits. Then, \( A_i \) forwards \((B_m, C_m)\) to the CSP to obtain the corresponding link \( \text{link}_m \), which costs \(|link| + 2|G| \) bits to transmit. If the received message “duplication \( B_m \)” , \( U \) does not need to upload any encrypted data. Finally, when the duplicate is found in the intra-deduplication, total overheads of data upload require \(|L| + 4|G| \) bits. If the duplicate is found in the inter-deduplication, then total overheads are \(|G| + 2|L| + |i| + |link| \) bits. Inversely, when the duplicate is not found, total overheads are \(|G| + 2|L| + |i| + |link| \) bits.

For data download, \( U \) sends “download \((T_m)\)” to \( A_i \) to obtain the corresponding link \( \text{link}_m \). Then, \( U \) downloads \( C_m \) from the
TABLE 1: The comparison of computational cost for uploading or downloading one data.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Upload</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duplicate in intra-dedup.</td>
<td>$3t_e + 2t_m + t_{mk} + 2t_p$</td>
<td>$4t_m + 6t_e + 4t_p$</td>
<td>–</td>
</tr>
<tr>
<td>Duplicate in inter-dedup.</td>
<td>$t_{mt} + 3t_m + 5t_e + 4t_p$</td>
<td>$4t_m + t_{mt} + (n + 7)t_e + (</td>
<td>S</td>
</tr>
<tr>
<td>Duplicate does not exist</td>
<td>$3t_m + 7t_e + t_{k1} + 2t_p$</td>
<td>$(</td>
<td>S</td>
</tr>
<tr>
<td>Search complexity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duplicate in intra-dedup.</td>
<td>$O(1)$</td>
<td>$O (\log_2</td>
<td>S_{all}</td>
</tr>
<tr>
<td>Duplicate in inter-dedup.</td>
<td>$O (\log_2</td>
<td>S_{all}</td>
<td>)$</td>
</tr>
<tr>
<td>Duplicate does not exist</td>
<td>$O (\log_2</td>
<td>S_{all}</td>
<td>)$</td>
</tr>
<tr>
<td>Data download</td>
<td>$t_e$</td>
<td>$t_{mt} + 3t_p$</td>
<td>$t_e + t_m$</td>
</tr>
</tbody>
</table>

TABLE 2: The comparison of communication overhead for uploading or downloading one data.

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Duplicate in intra-dedup.</td>
<td>$</td>
<td>L</td>
<td>+ 4</td>
</tr>
<tr>
<td>Duplicate in inter-dedup.</td>
<td>$7</td>
<td>G</td>
<td>+ 2</td>
</tr>
<tr>
<td>Duplicate does not exist</td>
<td>$3</td>
<td>G</td>
<td>+</td>
</tr>
<tr>
<td>Data download</td>
<td>$</td>
<td>link</td>
<td>+ \kappa_1$</td>
</tr>
</tbody>
</table>

TABLE 3: The comparison of storage cost.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_i$</td>
<td>$2\kappa_1 +</td>
<td>label</td>
<td>$</td>
</tr>
<tr>
<td>The CSP</td>
<td>$2</td>
<td>G</td>
<td>+</td>
</tr>
<tr>
<td>$C_m$</td>
<td>$3</td>
<td>G</td>
<td>+</td>
</tr>
</tbody>
</table>

CSP. Recall that $T_m$ is computed from the hash function $h_3 : \mathbb{G} \rightarrow \{0, 1\}^{\kappa_1}$, where $\kappa_1$ is the bit length of the convergent key. Hence, except for the $C_m$, additional overheads of data download require $|link| + \kappa_1$ bits.

2. Comparison of communication overhead. Table 2 presents the communication overheads of three schemes. Note that $\kappa_0$ is the security parameter and $\kappa_1$ is the bit length of the convergent key (see Section 4.1). $l$ is the bit length of short hash used in [8] and usually around 5 ~ 20 bits.

6.1.3 Storage Cost
In our scheme, after data upload, the user deletes the data $m$ and just stores $(T_m, c_k m, label_m)$, which needs $2\kappa_1 + |label|$ bits. After the intra-deduplication, if the duplicate exists, then $A_i$ does not need to store any data. Otherwise, $A_i$ records $(T_m, B_{mk}, link_m)$ with $2|G| + |link| + \kappa_1$ bits in length. Similarly, if the duplication exists in the inter-deduplication, the CSP would not store any data. Otherwise, the CSP stores the outsourced data $(i, L_m, T_m, B_m, C_m)$. Except for the symmetric ciphertext $C_m$, the additional storage costs for the CSP are $3|G| + |L| + |i|$ bits.

Table 3 shows the storage costs of the three schemes. Note that $|label|$ represents the bit length of the data’s label.

6.2 Simulation analysis
In this section, we discuss the simulation analysis and give a comparison of three schemes. Specifically, we conduct experiments with PBC [31] and OpenSSL [32] libraries running on a 2.6 GHz-processor 2 GB-memory computing machine.

6.2.1 Simulation setup
In the simulation, we instantiate the bilinear pairing with type A1, i.e., $\kappa_0 = 512$ bits. We set the bit length of the convergent key to be 256 bits, i.e., $\kappa_1 = 256$ bits. We also set $|i| = |L| = 64$ bits, $|link| = 2048$ bits and $|label| = 1024$ bits. Note that, since $|link|$ represents the bit length of the file path, 256-bytes is sufficient to represent the usual path. Recall $label_m$ is the label of the data $m$, e.g., the name or feature used for identifying the data $m$, thus 1024 bits are enough for the $label_m$. In addition, as introduced in [8], $l$ is usually around 5 ~ 20 bits, thus we directly set $l = 20$ bits.

For the setting of variables, suppose each user uploads or downloads $k$ data, wherein $k \psi$ data are duplicates and $k \psi \cdot \mu$ out of $k \psi$ duplicates are found during the intra-deduplication. Note that $0 \leq \psi, \mu \leq 1$. In what follows, we analyze how the computational cost, communication overhead and storage cost change as uploaded or downloaded data number $k$, duplication ratio $\psi$, domain number $n$ and the duplication ratio in the intra-deduplication $\mu$.

6.2.2 Simulation results
1. Computational cost. We depict the comparison of computational costs in Fig. 4. Specifically, Fig. 4(a)–4(e) show the variation of operation cost in terms of $k$, $n$, $\psi$, and $\mu$. Fig. 4(f)–4(h) show the variation of the duplicate search complexity in terms of total stored data number $|S_{all}|$ and the order of the DDT $f$ (or disjoint subset number $2^l$ in [8]).

From Fig. 4, we can see that the computational efficiency of our scheme is much better than the other two schemes for all variables. The main reasons are two aspects: the efficiency of ciphertext calculations and the duplicate search complexity. On the one hand, for ensuring that the outsourced data can be correctly decrypted by users with ownership, our scheme only contains a constant number of ciphertexts, i.e., a symmetric ciphertext $C_m$ and a key-encapsulated ciphertext $B_m$ with two elements in $G$. However, in the scheme [8], except for the symmetric ciphertext, the key-encapsulated ciphertexts...
Data upload.

Inter-deduplication.

Computational cost (s)

Search complexity

Fig. 4: The comparison of computational cost.

\[ \{e(H(m)^s, g)^{r_1}(g^{\frac{1}{n}})^{r_2}, \ldots, (g^{\frac{1}{n}})^{r_{n}}\} \] contain one element in \( G_T \) and \( n \) elements in \( G \), which increases linearly with \( n \). Thus, our scheme can significantly reduce the computational costs of data encryption, as shown in Fig. 4(a)-4(d). Note that, in the scheme [30], it directly uses the hash value of the data \( m \) as the main key to obtain the symmetric key. In other words, as long as the user has \( h(m) \), the symmetric key selected by the initial uploader can be obtained correctly. Thus, this scheme would not introduce a large number of additional ciphertexts as in the scheme [8]. However, it is clear that this scheme is not resistant to brute-force attacks. On the other hand, in the intra-deduplication, our scheme constructs a hash table to find the duplicate, where the search complexity is \( O(1) \). But the scheme [8] uses a binary search tree to store the tag, where the search complexity is \( O(\log_2 |S_{D_i}|) \). For convenience, we directly set \(|S_{D_i}| = |S_{all}|/n \). Obviously, the search complexity of our scheme is more efficient than the scheme [8], as shown in Fig. 4(f). For the inter-deduplication, our scheme constructs the DDT based on the B+ tree, where the search complexity is \( O(\log_f |S_{all}|) \). The scheme [30] uses the binary search tree to find the duplicate, where the search complexity is \( O(\log_2 |S_{all}|) \). However, the scheme [8] introduces a short hash to divide the set \( S_{all} \) into \( 2^l \) subsets, and thus the search complexity is sub-linear, i.e., \( O(|S_{all}|/2^l) \). In general, the logarithmic search complexity is more efficient than the sub-linear complexity, while the complexity of the B+ tree is more efficient than the binary search tree. Therefore, the search complexity of our scheme is more efficient than the other two, as shown in Fig. 4(g) and 4(h).

For data download, the costs of our scheme and Jiang et al’s scheme [30] are less than the Shin’s scheme [8] for \( k \), as shown in Fig. 4(e). The reason is that our scheme achieves data verification by computing \( T_{m^*} = h_3(d_3^{2k(m^*)}) \). However, the scheme [8] needs to verify whether \( e(g,t_m) = e(H(m^*), g^{\psi}) \) holds. Note that, the scheme [30] does not consider data verification. The resulting costs are related to the recovery of the symmetric key.

2. Communication overhead. In Fig. 5, we plot the comparison of communication overheads in terms of \( k, n, \psi, \) and \( \mu \). It is shown that our scheme significantly reduces communication overheads compared with the scheme [8]. Similar to the analysis of computational cost, the main reason is that our scheme only sends a constant number of ciphertexts to the CSP. However, for the scheme [8], the number of uploaded or downloaded ciphertexts is linear with \( n \), which will cause more communication overheads, especially when \( n \) increases, as shown in Fig. 5(b). The communication overhead of our scheme is slightly larger than the scheme [30]. The reason is that we introduce the agent between users and the CSP to perform the intra-deduplication and forward the received messages to the CSP or users, which will increase communication overheads.

3. Storage cost. Fig. 6 shows the comparison of storage costs for these three schemes in terms of \( k, n, \psi, \) and \( \mu \). It is shown that our scheme reduces storage costs compared with the scheme [8]. The main reason is that the number of ciphertexts generated in our scheme is constant. Note that for the convenience of comparison, we summarize the storage cost of \( A_i \) to the CSP for analysis. Due to the introduction of the agent, the storage cost of our scheme is slightly larger than the scheme [30], as shown in Fig. 6(b)-6(d). But, this process helps greatly improve the efficiency of the duplicate search if the data come from the same domain, as shown in Fig. 4. More importantly, the agent can maintain a rating-limiting strategy to resist the online brute-force attacks launched by malicious users.

From the above analyses, our scheme is indeed efficient in terms of computational, communication and storage overheads compared with the up-to-date works, which shows the significance and practical potential of our scheme to support big data.
deduplication and storage.

7 RELATED WORK

Secure data deduplication technique, as it can eliminate redundant data while achieving data confidentiality, has been widely developed by the research community [12]. The convergent encryption (CE) was the first solution that can achieve deduplication over encrypted data [3], [33]. In the CE, data is encrypted by its hash value and the corresponding tag is produced by hashing the generated ciphertext. Clearly, when different users independently encrypt the same data, they will generate the same ciphertexts and tags which can be easily deduplicated. However, the precise security guarantee of the CE was never fully proven or even stated. After that, Bellare et al. [4] formalized the CE a new cryptographic primitive called message-locked encryption (MLE) and gave a semantic security proof for unpredictable messages. Unfortunately, for predictable messages, the MLE (as well as the CE) is vulnerable to brute-force attacks due to its deterministic property [5].

In order to resist brute-force attacks, Bellare et al. [5] firstly proposed a server-aided secure deduplication scheme, called DupLESS, based on the RSA-OPRF (Oblivious Pseudo-Random Function) protocol [34]. In DupLESS, each user interacts with a centralized key server (KS) to obtain the corresponding convergent key for each uploaded data. Obviously, this centralized-KS should be always online to response key generation requests sent from users in the system. Thus, it is very vulnerable to the single point of failure, i.e., once the KS is compromised, the security of the DupLESS totally degrades into the MLE algorithm. To deal with this issue, Miao et al. [6] presented a multi-server-aided secure deduplication scheme based on a threshold blind signature [35]. In this scheme, each user interacts with at least a threshold number of KSs to generate a convergent key. Besides, Duan et al. [7] introduced a distributed key generation protocol based on the RSA threshold signature [36]. Unlike the scheme proposed in [6], this scheme employed a trusted dealer to distribute key shares for online users in the system and each user interacts with at least a threshold number of online users to acquire a convergent key. The trusted dealer plays a similar role to that of the KS in DupLESS, but it participates only in the system setup phase. In both schemes, as long as the number of compromised KSs or online users does not exceed the threshold, the security can be preserved. Unfortunately, both two schemes only can deal with the intra-deduplication, i.e., they can only remove the redundancy among outsourced data that correspond to the same KSs or users (i.e., the same domain in our system). In order to extend the deduplication into the cross-domain, Shin et al. [8] recently constructed an inter-deduplication scheme based on the Boldyreva’s blind signature [37]. In this scheme, even private keys chosen by different KSs are different, the CSP can still eliminate the redundancy among outsourced data from different domains. However, since different outsourced data are encrypted by different private keys, in order to ensure these data can be correctly decrypted by users with the ownership, for each uploaded data, the number of corresponding ciphertexts is linear with the number of domains. Thus, massive computational, communication and storage overheads are incurred when the number of domains explodes.

In addition to the semantic security of encrypted data and tags, the message equality information of outsourced data (i.e., the information whether two different ciphertexts correspond to an
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identical plaintext) needs to be protected as much as possible. For example, Stanek et al. [9] added a trusted third party, index repository service (IRS), to complete the duplication judgment. That is, only the IRS can know the message equality information. Thus, this scheme can prevent other entities from obtaining the message equality information. However, the assumption of a trusted IRS is too strong to be accepted in practice. Furthermore, the IRS seems vulnerable because it should be always online to deal with data upload requests. Accordingly, this scheme is vulnerable to offline brute-force attacks when the IRS is compromised [11].

To improve these disadvantages, Yang et al. [10] proposed an efficient deduplication scheme that achieves data confidentiality while resisting brute-force attacks. Without requiring an additional trusted server in this scheme, any adversary excluding the CSP cannot know the message equality information, i.e., only the CSP can decide whether two given tags from different domains correspond to the same data or not. However, this scheme only can deduplicate for outsourced data from two different domains.

8 Conclusion

In this paper, we have proposed an efficient and privacy-preserving big data deduplication scheme for a two-level multi-domain architecture. Specifically, our scheme can achieve the semantic security of encrypted data while ensuring that the outsourced encrypted data can be correctly decrypted by users with ownership by generating a constant number of ciphertexts. Besides, only the CSP (the agent) can decide whether two given random inter-tags from different domains (intra-tags from the same domain) correspond to the same data or not, which minimizes the disclosure of the message equality information. Detailed security analyses demonstrate that our scheme can achieve data confidentiality and data integrity while resisting brute-force attacks. Furthermore, extensive performance evaluations show that our scheme outperforms the existing competing schemes, especially the computational cost and the time complexity of the duplicate search.

Future research includes extending the proposed scheme to achieve the ownership management and revocation because data modification or deletion operations are often requested by users. Moreover, since data deduplication techniques keep only one copy of the data, outsourced data after deduplication is vulnerable to data loss or corruption. Accordingly, future research agenda will also include extending the proposed scheme to address the reliability of outsourced data.

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