

CDStore: Toward Reliable, Secure, and Cost-Efficient Cloud Storage via Convergent Dispersal

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Abstract

We present *CDStore*, which disperses users' backup data across multiple clouds and provides a unified multi-cloud storage solution with reliability, security, and cost-efficiency guarantees. *CDStore* builds on an augmented secret sharing scheme called *convergent dispersal*, which supports deduplication by using deterministic content-derived hashes as inputs to secret sharing. We present the design of *CDStore*, and in particular, describe how it combines convergent dispersal with two-stage deduplication to achieve both bandwidth and storage savings and be robust against side-channel attacks. We evaluate the performance of our *CDStore* prototype using real-world workloads on LAN and commercial cloud testbeds. Our cost analysis also demonstrates that *CDStore* achieves a monetary cost saving of 70% over a baseline cloud storage solution using state-of-the-art secret sharing.

1 Introduction

Cloud storage provides cost-efficient means for organizations to host backups off-site [40]. However, from users' perspectives, putting all data in one cloud raises *reliability* concerns regarding the single point of failure [8] and vendor lock-in [5], especially when cloud storage providers can spontaneously terminate their business [35]. Cloud storage also raises *security* concerns, since data management is now outsourced to third parties. Users often want their outsourced data to be protected with guarantees of *confidentiality* (i.e., data is kept secret from unauthorized parties) and *integrity* (i.e., data is uncorrupted).

Multi-cloud storage coalesces multiple public cloud storage services into a single storage pool, and provides a plausible way to realize both reliability and security in outsourced storage. It disperses data with some form of redundancy across multiple clouds, operated by independent vendors, such that the stored data can be recovered from a subset of clouds even if the remaining clouds are unavailable. Redundancy can be realized through *erasure coding* (e.g., Reed-Solomon codes [51]) or *secret sharing* (e.g., Shamir's scheme [54]). Recent multi-

cloud storage systems (e.g., [5, 19, 29, 33, 60]) leverage erasure coding to tolerate cloud failures, but do not address security; DepSky [13] uses secret sharing to further achieve both reliability and security. Secret sharing often comes with high redundancy, yet its variants are shown to reduce the redundancy of secret sharing to be slightly higher than that of erasure coding, while achieving security in the computational sense (see §2). Secret sharing has a side benefit of providing *keyless* security (i.e., eliminating encryption keys), which builds on the difficulty for an attacker to compromise multiple cloud services rather than a secret key. This removes the key management overhead as found in key-based encryption [56].

However, existing secret sharing algorithms prohibit storage savings achieved by *deduplication*. Since backup data carries substantial identical content [58], organizations often use deduplication to save storage costs, by keeping only one physical data copy and having it shared by other copies with identical content. On the other hand, secret sharing uses random pieces as inputs when generating dispersed data. Users embed different random pieces, making the dispersed data different even if the original data is identical.

This paper presents a new multi-cloud storage system called *CDStore*, which makes the first attempt to provide a unified cloud storage solution with reliability, security, and cost efficiency guarantees. *CDStore* builds on our prior proposal of an enhanced secret sharing scheme called *convergent dispersal* [37], whose core idea is to replace the random inputs of traditional secret sharing with deterministic cryptographic hashes derived from the original data, while the hashes cannot be inferred by attackers without knowing the whole original data. This allows deduplication, while preserving the reliability and keyless security features of secret sharing. Using convergent dispersal, *CDStore* offsets dispersal-level redundancy due to secret sharing by removing content-level redundancy via deduplication, and hence achieves cost efficiency. To summarize, we extend our prior work [37] and make three new contributions.

First, we propose a new instantiation of convergent dispersal called *CAONT-RS*, which builds on AONT-RS [52]. *CAONT-RS* maintains the properties of AONT-RS, and makes two enhancements: (i) using OAEP-based

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AONT [20] to improve performance and (ii) replacing random inputs with deterministic hashes to allow deduplication. Our evaluation also shows that CAONT-RS generates dispersed data faster than our prior AONT-RS-based instantiation [37].

Second, we present the design and implementation of CDStore. It adopts *two-stage deduplication*, which first deduplicates data of the same user on the client side to save upload bandwidth, and then deduplicates data of different users on the server side to further save storage. Two-stage deduplication works seamlessly with convergent dispersal, achieves bandwidth and storage savings, and is robust against side-channel attacks [27, 28]. We also carefully implement CDStore to mitigate computation and I/O bottlenecks.

Finally, we thoroughly evaluate our CDStore prototype using both microbenchmarks and trace-driven experiments. We use real-world backup and virtual image workloads, and conduct evaluation on both LAN and commercial cloud testbeds. We show that CAONT-RS encoding achieves around 180MB/s with only two-thread parallelization. We also identify the bottlenecks when CDStore is deployed in a networked environment. Furthermore, we show via cost analysis that CDStore can achieve a monetary cost saving of 70% via deduplication over AONT-RS-based cloud storage.

2 Secret Sharing Algorithms

We conduct a study of the state-of-the-art secret sharing algorithms. A secret sharing algorithm operates by transforming a data input called *secret* into a set of coded outputs called *shares*, with the primary goal of providing both fault tolerance and confidentiality guarantees for the secret. Formally, a secret sharing algorithm is defined based on three parameters (n, k, r) : *an (n, k, r) secret sharing algorithm (where $n > k > r \geq 0$) disperses a secret into n shares such that (i) the secret can be reconstructed from any k shares, and (ii) the secret cannot be inferred (even partially) from any r shares.*

The parameters (n, k, r) define the protection strength of a secret sharing algorithm. Specifically, n and k determine the fault tolerance degree of a secret, such that the secret remains available as long as any k out of n shares are accessible. In other words, it can tolerate the loss of $n - k$ shares. The parameter r determines the confidentiality degree of a secret, such that the secret remains confidential as long as no more than r shares are compromised by an attacker. On the other hand, a secret sharing algorithm makes the trade-off of incurring additional storage. We define the *storage blowup* as the ratio of the total size of n shares to the size of the original secret. Note that the storage blowup must be at least $\frac{n}{k}$, as the secret is recoverable from any k out of n shares.

Several secret sharing algorithms have been proposed

Algorithm	Confidentiality degree	Storage blowup [†]
SSSS [54]	$r = k - 1$	n
IDA [50]	$r = 0$	$\frac{n}{k}$
RSSS [16]	$r \in [0, k - 1]$	$\frac{n}{k-r}$
SSMS [34]	$r = k - 1$	$\frac{n}{k} + n \cdot \frac{S_{key}}{S_{sec}}$
AONT-RS [52]	$r = k - 1$	$\frac{n}{k} + \frac{n}{k} \cdot \frac{S_{key}}{S_{sec}}$

[†] S_{sec} : size of a secret; S_{key} : size of a random key.

Table 1: Comparison of secret sharing algorithms.

in the literature. Table 1 compares them in terms of the confidentiality degree and the storage blowup, subject to the same n and k . Two extremes of secret sharing algorithms are Shamir’s secret sharing scheme (SSSS) [54] and Rabin’s information dispersal algorithm (IDA) [50]. SSSS achieves the highest confidentiality degree (i.e., $r = k - 1$), but its storage blowup is n (same as replication). IDA has the lowest storage blowup $\frac{n}{k}$, but its confidentiality degree is the weakest (i.e., $r = 0$), and any share can reveal the information of the secret. Ramp secret sharing scheme (RSSS) [16] generalizes both IDA and SSSS to make a trade-off between the confidentiality degree and the storage blowup. It evenly divides a secret into $k - r$ pieces, and generates r additional random pieces of the same size. It then transforms the k pieces into n shares using IDA.

Secret sharing made short (SSMS) [34] combines IDA and SSSS using traditional key-based encryption. It first encrypts the secret with a random key and then disperses the encrypted secret and the key using IDA and SSSS, respectively. Its storage blowup is slightly higher than that of IDA, while it has the highest confidentiality degree $r = k - 1$ as in SSSS. Note that the confidentiality degree is defined in the computational sense, that is, it is computationally infeasible to break the encryption algorithm without knowing the key.

AONT-RS [52] further reduces the storage blowup of SSMS, while preserving the highest confidentiality degree $r = k - 1$ (in the computational sense). It combines Rivest’s all-or-nothing transform (AONT) [53] for confidentiality and Reed-Solomon coding [17, 51] for fault tolerance. It first transforms the secret into an AONT package with a random key, such that an attacker cannot infer anything about the AONT package unless the whole package is obtained. Specifically, it splits a secret into a number $s \geq 1$ of words, and adds an extra *canary* word for integrity checking. It masks each of the s words by XOR’ing it with an index value encrypted by a random key. The s masked words are placed at the start of an AONT package. One more word, obtained by XOR’ing the same random key with the hash of the masked words, is added to the end of the AONT package. The final AONT package is then divided into k equal-size shares, which are encoded into n shares using a *system-*

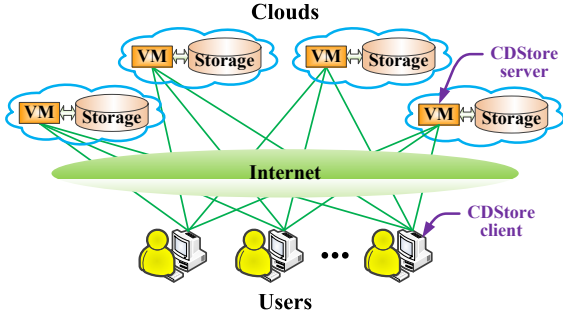


Figure 1: CDStore architecture.

atic Reed-Solomon code (a systematic code means that the n shares include the original k shares).

The security of existing secret sharing algorithms lies in the embedded random inputs (e.g., a random key in AONT-RS). Due to randomness, secrets with identical content lead to distinct sets of shares, thereby prohibiting deduplication. This motivates CDStore, which enables secret sharing with deduplication.

3 CDStore Design

CDStore is designed for an organization to outsource the storage of data of a large group of users to multiple cloud vendors. It builds on the client-server architecture, as shown in Figure 1. Each user of the same organization runs the *CDStore client* to store and access its data in multiple clouds over the Internet. In each cloud, a co-locating virtual machine (VM) instance owned by the organization runs the *CDStore server* between multiple CDStore clients and the cloud storage backend.

CDStore targets backup workloads. We consider a type of backups obtained by snapshotting some applications, file systems, or virtual disk images. Backups generally have significant identical content, and this makes deduplication useful. Field measurements on backup workloads show that deduplication can reduce the storage overhead by $10\times$ on average, and up to $50\times$ in some cases [58]. In CDStore deployment, each user machine submits a series of backup files (e.g., in UNIX `tar` format) to the co-located CDStore client, which then processes the backups and uploads them to all clouds.

3.1 Goals and Assumptions

We state the design goals and assumptions of CDStore in three aspects: reliability, security, and cost efficiency.

Reliability: CDStore tolerates failures of cloud storage providers and even CDStore servers. Outsourced data is accessible if a tolerable number of clouds (and their co-locating CDStore servers) are operational. CDStore also tolerates client-side failures by offloading metadata management to the server side (see §4.3). In the presence of cloud failures, CDStore reconstructs original secrets and then rebuilds the lost shares as in Reed-Solomon codes [51]. We do not consider cost-efficient repair [29].

Security: CDStore exploits multi-cloud diversity to ensure *confidentiality* and *integrity* of outsourced data against outsider attacks, as long as a tolerable number of clouds are uncompromised. Note that the confidentiality guarantee requires that the secrets be drawn from a very large message space, so that brute-force attacks are infeasible [10]. CDStore also uses two-stage deduplication (see §3.3) to avoid insider side-channel attacks [27, 28] launched by malicious users. Here, we do not consider strong attack models, such as Byzantine faults in cloud services [13]. We also assume that the client-server communication over the network is protected, so that an attacker cannot infer the secrets by eavesdropping the transmitted shares.

Cost efficiency: CDStore uses deduplication to reduce both bandwidth and storage costs. It also incurs limited overhead in computation (e.g., VM usage) and storage (e.g., metadata). We assume that there is no billing for the communication between a co-locating VM and the storage backend of the same cloud, based on today’s pricing models of most cloud vendors [30].

3.2 Convergent Dispersal

Convergent dispersal enables secret sharing with deduplication by replacing the embedded random input with a deterministic cryptographic hash derived from the secret. Thus, two secrets with identical content must generate identical shares, making deduplication possible. Also, it is computationally infeasible to infer the hash without knowing the whole secret. Our idea is inspired by convergent encryption [24] used in traditional key-based encryption, in which the random key is replaced by the cryptographic hash of the data to be encrypted. Figure 2 shows the main idea of how we augment a secret sharing algorithm with convergent dispersal.

This paper proposes a new instantiation of convergent dispersal called *CAONT-RS*, which inherits the reliability and security properties of the original AONT-RS, and makes two key modifications. First, to improve performance, CAONT-RS replaces Rivest’s AONT [53] with another AONT based on *optimal asymmetric encryption padding (OAEP)* [11, 20]. The rationale is that Rivest’s AONT performs multiple encryptions on small-size words (see §2), while OAEP-based AONT performs a single encryption on a large-size, constant-value block. Also, OAEP-based AONT provably provides no worse security than any AONT scheme [20]. Second, CAONT-RS replaces the random key in AONT with a deterministic cryptographic hash derived from the secret. Thus, it preserves content similarity in dispersed shares and allows deduplication. Our prior work [37] also proposes instantiations for RSSS [16] and AONT-RS (based on Rivest’s AONT) [52]. Our new CAONT-RS shows faster encoding performance than our prior AONT-RS-based instantiation (see §5.3).

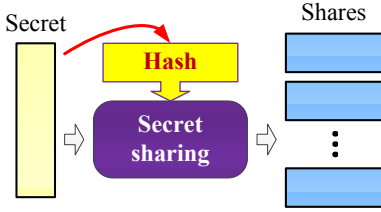


Figure 2: Idea of convergent dispersal.

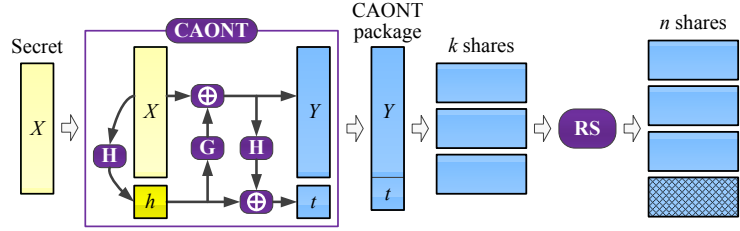


Figure 3: Example of CAONT-RS with $n = 4$ and $k = 3$.

We now elaborate on the encoding and decoding of CAONT-RS, both of which are performed by a CDStore client. Figure 3 shows an example of CAONT-RS with $n = 4$ and $k = 3$ (and hence $r = k - 1 = 2$).

Encoding: We first transform a given secret X into a CAONT package. Specifically, we first generate a hash key h , instead of a random key, derived from X using a (optionally salted) hash function \mathbf{H} (e.g., SHA-256):

$$h = \mathbf{H}(X). \quad (1)$$

To achieve confidentiality, we transform (X, h) into a CAONT package (Y, t) using OAEP-based AONT, where Y and t are the head and tail parts of the CAONT package and have the same size as X and h , respectively. To elaborate, Y is generated by:

$$Y = X \oplus \mathbf{G}(h), \quad (2)$$

where \oplus is the XOR operator and \mathbf{G} is a generator function that takes h as input and constructs a mask block with the same size as X . Here, we implement the generator \mathbf{G} as:

$$\mathbf{G}(h) = \mathbf{E}(h, C), \quad (3)$$

where C is a constant-value block with the same size as X , and \mathbf{E} is an encryption function (e.g., AES-256) that encrypts C using h as the encryption key.

The tail part t is generated by:

$$t = h \oplus \mathbf{H}(Y). \quad (4)$$

Finally, we divide the CAONT package into k equal-size shares (we pad zeroes to the secret if necessary to ensure that the CAONT package can be evenly divided). We encode them into n shares using the systematic Reed-Solomon codes [17, 46, 47, 51].

To enable deduplication, we ensure that the same share is located in the same cloud. Since the number of clouds for multi-cloud storage is usually small, we simply disperse shares to all clouds. Suppose that CDStore spans n clouds, which we label $0, 1, \dots, n - 1$. After encoding each secret using convergent dispersal, we label the n generated shares $0, 1, \dots, n - 1$ in the order of their positions in the Reed-Solomon encoding result, such that share i is to be stored on cloud i , where $0 \leq i \leq n - 1$.

This ensures that the same cloud always receives the same share from the secrets with identical content, either generated by the same user or different users. This also enables us to easily locate the shares during restore.

Decoding: To recover the secret, we retrieve any k out of n shares and use them to reconstruct the original CAONT package (Y, t) . Then we deduce hash h by XOR'ing t with $\mathbf{H}(Y)$ (see Equation (4)). Finally, we deduce secret X by XOR'ing Y with $\mathbf{G}(h)$ (see Equation (2)), and remove any padded zeroes introduced in encoding.

We can also verify the integrity of the deduced secret X . We simply generate a hash value from the deduced X as in Equation (1) and compare if it matches h . If the match fails, then the decoded secret is considered to be corrupted. To obtain a correct secret, we can follow a brute-force approach, in which we try a different subset of k shares until the secret is correctly decoded [19].

Remarks: We briefly discuss the security properties of CAONT-RS. CAONT-RS ensures confidentiality against outsider attacks, provided that an attacker cannot gain unauthorized accesses to k out of n clouds, and ensures integrity through the embedded hash in each secret. It leverages AONT to ensure that no information of the original secret can be inferred from fewer than k shares. We note that an attacker can identify the deduplication status of the shares of different users and perform brute-force dictionary attacks [9, 10] inside the clouds, and we require that the secrets be drawn from a large message space (see §3.1). To mitigate brute-force attacks, we may replace the hash key in CAONT-RS with a more sophisticated key generated by a key server [9], with the trade-off of introducing the key management overhead.

3.3 Two-Stage Deduplication

We first overview how deduplication works. Deduplication divides data into fixed-size or variable-size *chunks*. This work assumes variable-size chunking, which defines boundaries based on content and is robust to content shifting. Each chunk is uniquely identified by a *fingerprint* computed by a cryptographic hash of the chunk content. Two chunks are said to be identical if their fingerprints are the same, and fingerprint collisions of two different chunks are very unlikely in practice [15]. Deduplication stores only one copy of a chunk, and refers any

duplicate chunks to the copy via small-size references.

To realize deduplication in cloud storage, a naïve approach is to perform global deduplication on the client side. Specifically, before a user uploads data to a cloud, it first generates fingerprints of the data. It then checks with the cloud by fingerprint for the existence of any duplicate data that has been uploaded by any user. Finally, it uploads only the unique data to the cloud. Although client-side global deduplication saves upload bandwidth and storage overhead, it is susceptible to *side-channel attacks* [27, 28]. One side-channel attack is to infer the existence of data of other users [28]. Specifically, an attacker generates the fingerprints of some possible data of other users and queries the cloud by fingerprint if such data is unique and needs to be uploaded. If no upload is needed, then the attacker infers that other users own the data. Another side-channel attack is to gain unauthorized access to data of other users [27]. Specifically, an attacker uses the fingerprints of some sensitive data of other users to convince the cloud of the data ownership.

To prevent side-channel attacks, CDStore adopts *two-stage deduplication*, which eliminates duplicates first on the client side and then on the server side. We require that each CDStore server maintains a deduplication index that keeps track of which shares have been stored by each user and how shares are deduplicated (see implementation details in §4.4). Then the two deduplication stages are implemented as follows.

Intra-user deduplication: A CDStore client first runs deduplication only on the data owned by the same user, and uploads the unique data of the user to the cloud. Before uploading shares to a cloud, the CDStore client first checks with the CDStore server by fingerprint if it has already uploaded the same shares. Specifically, the CDStore client first sends the fingerprints generated from the shares to the CDStore server. The CDStore server then looks up its deduplication index, and replies to the CDStore client a list of share identifiers that indicate which shares have been uploaded by the CDStore client. Finally, the CDStore client uploads only unique shares to the cloud based on the list.

Inter-user deduplication: A CDStore server runs deduplication on the data of all users and stores the globally unique data in the cloud storage backend. After the CDStore server receives shares from the CDStore client, it generates a fingerprint from each share (instead of using the one generated by the CDStore client for intra-user deduplication), and checks if the share has already been stored by other users by looking up the deduplication index. It stores only the unique shares that are not yet stored at the cloud backend. It also updates the deduplication index to keep track of which user owns the shares. Here, we cannot directly use the fingerprint generated by the CDStore client for intra-user deduplication.

Otherwise, an attacker can launch a side-channel attack, by using the fingerprint of a share of other users to gain unauthorized access to the share [27, 43].

Remarks: Two-stage deduplication prevents side-channel attacks by making deduplication patterns independent across users' uploads. Thus, a malicious insider cannot infer the data content of other users through deduplication occurrences.

Both intra-user and inter-user deduplications effectively remove duplicates. Intra-user deduplication eliminates duplicates of the same user's data. This is effective for backup workloads, since the same user often makes repeated backups of the same data as different versions [32]. Inter-user deduplication further removes duplicates of multiple users. For example, multiple users within the same organization may share a large proportion of business files. Some workloads exhibit large proportions of duplicates across different users' data, such as VM images [31], workstation file system snapshots [42], and backups [58]. The removal of duplicates translates to cost savings (see §5.6).

4 CDStore Implementation

We present the implementation details of CDStore. Our CDStore prototype is written in C++ on Linux. We use OpenSSL [4] to implement cryptographic operations: AES-256 and SHA-256 for the encryption and hash algorithms of convergent dispersal, respectively, and SHA-256 for fingerprints in deduplication. We use GF-Complete [48] to accelerate Galois Field arithmetic in the Reed-Solomon coding of CAONT-RS.

4.1 Architectural Overview

We follow a modular approach to implement CDStore, whose client and server architectures are shown in Figure 4. During file uploads, a CDStore client splits the file into a sequence of secrets via the *chunking module*. It then encodes each secret into n shares via the *coding module*. It performs intra-user deduplication, and uploads unique shares to the CDStore servers in n different clouds via both client-side and server-side *communication modules*. To reduce network I/Os, we avoid sending many small-size shares over the Internet. Instead, we first batch the shares to be uploaded to each cloud in a 4MB buffer and upload the buffer when it is full. Upon receiving the shares, each CDStore server performs inter-user deduplication via the *deduplication module* and updates the deduplication metadata via the *index module*. Finally, it packs the unique shares as containers and writes the containers to the cloud storage backend through the internal network via the *container module*.

File downloads work in the reverse way. A CDStore client connects to any k clouds to request to download a file. Each CDStore server retrieves the corresponding containers and metadata, and returns all required shares

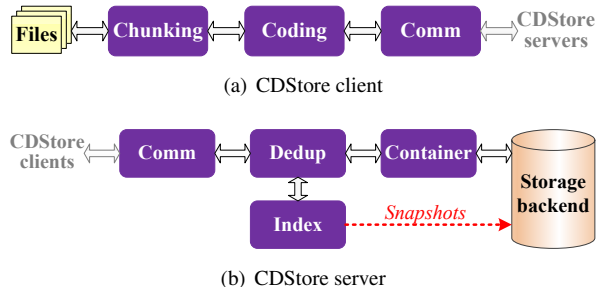


Figure 4: Implementation of the CDStore architecture.

and file metadata. The CDStore client decodes the secrets and assembles the secrets back to the file.

4.2 Chunking

We implement both fixed-size chunking and variable-size chunking in the chunking module of a CDStore client, and enable variable-size chunking by default. To make deduplication effective, the size of each secret should be on the order of kilobytes (e.g., 8KB [62]). We implement variable-size chunking based on Rabin fingerprinting [49], in which the average, minimum, and maximum secret (chunk) sizes are configured at 8KB, 2KB, and 16KB, respectively.

4.3 Metadata Offloading

One important reliability requirement is to tolerate client-side failures, as we expect that a CDStore client is deployed in commodity hardware. Thus, our current implementation makes CDStore servers keep and manage all metadata on behalf of CDStore clients.

When uploading a file, a CDStore client collects two types of metadata. First, after chunking, it collects *file metadata* for the upload file, including the full pathname, file size, and number of secrets. Second, after encoding a secret into shares, it collects *share metadata* for each share, including the share size, fingerprint of the share (for intra-user deduplication), sequence number of the input secret, and secret size (for removing padded zeroes when decoding the original secret).

The CDStore client uploads the file and share metadata to the CDStore servers along with the uploaded file. The metadata will serve as input for each CDStore server to maintain index information (see §4.4).

We distribute metadata across all CDStore servers for reliability. For non-sensitive information (e.g., the size and sequence number of each secret), we can simply replicate it, so that each CDStore server can directly use it to manage data transfer and deduplication. However, for sensitive information (e.g., a file’s full pathname), we encode and disperse it via secret sharing.

4.4 Index Management

Each CDStore server uses the metadata from CDStore clients to generate index information of the uploaded

files and keep it in the index module. There are two types of index structures: the *file index* and the *share index*.

The file index holds the entries for all files uploaded by different users. Each entry describes a file, identified by the full pathname (which has been encoded as described in §4.3) and the user identifier provided by a CDStore client. We hash the full pathname and the user identifier to obtain a unique key for the entry. The entry stores a reference to the *file recipe*, which describes the complete details of the file, including the fingerprint of each share (for retrieving the share) and the size of the corresponding secret (for decoding the original secret). The file recipe will be saved at the cloud backend by the container module (see §4.5).

The share index holds the entries for all unique shares of different files. Each entry describes a share, and is keyed by the share fingerprint. It stores the reference to the container that holds the share. To support intra-user deduplication, each entry also holds a list of user identifiers to distinguish who owns the share, as well as a reference count for each user to support deletion.

Our prototype manages file and share indices using LevelDB [26], an open-source key-value store. LevelDB maintains key-value pairs in a log-structured merge (LSM) tree [44], which supports fast random inserts, updates, and deletes, and uses a Bloom filter [18] and a block cache to speed up lookups. We can also leverage the snapshot feature provided by LevelDB to store periodic snapshots in the cloud backend for reliability. We currently do not consider this feature in our evaluation.

4.5 Container Management

The container module maintains two types of containers in the storage backend: *share containers*, which hold the globally unique shares, and *recipe containers*, which hold the file recipes of different files. We cap the container size at 4MB, except that if a file recipe is very large (due to a particularly large file), we keep the file recipe in a single container and allow the container to go beyond 4MB. We avoid splitting a file recipe in multiple containers to reduce I/Os.

We make two optimizations to reduce the I/O overhead of storing and fetching the containers via the storage backend. First, we maintain in-memory buffers for holding shares and file recipes before writing them into containers. We organize the shares or file recipes by users, so that each container contains only the data of a single user. This retains spatial locality of workloads [62]. Second, we maintain a least-recently-used (LRU) disk cache to hold the most recently accessed containers to reduce I/Os to the storage backend.

4.6 Multi-Threading

Advances of multi-core architectures enable us to exploit multi-threading for parallelization. First, the client-

side coding module uses multi-threading for the CPU-intensive encoding/decoding operations of CAONT-RS. We parallelize encoding/decoding at the secret level: in file uploads, we pass each secret output from the chunking module to one of the threads for encoding; in file downloads, we pass the shares of a secret received by the communication module to a thread for decoding.

Furthermore, both client-side and server-side communication modules use multi-threading to fully utilize the network transfer bandwidth. The client-side communication module creates multiple threads, one for each cloud, to upload/download shares. The server-side communication module also uses multiple threads to send/receive shares for different CDStore clients.

4.7 Open Issues

Our current CDStore prototype implements the basic backup and restore operations. We discuss some open implementation issues.

Storage efficiency: We can reclaim more storage space via different techniques in addition to deduplication. For example, garbage collection can reclaim space of expired backups. By exploiting historical information, we can accelerate garbage collection in deduplication storage [25]. Compression also effectively reduces storage space of both data [58] and metadata (e.g., file recipes [41]). Implementations of garbage collection and compression are posed as future work.

Scalability: We currently deploy one CDStore server per cloud. In large-scale deployment, we can run CDStore servers on multiple VMs per cloud and evenly distribute user backup jobs among them for load balance. Implementing a distributed deduplication system is beyond the scope of this paper.

Consistency: Our prototype is tailored for backup workloads that are immutable. We do not address consistency issues due to concurrent updates as mentioned in [13].

5 Evaluation

We evaluate CDStore under different testbeds and workloads. We also analyze its monetary cost advantages.

5.1 Testbeds

We consider three types of testbeds in our evaluation.

(i) *Local machines:* We use two machines: *Local-Xeon*, which has a quad-core 2.4GHz Intel Xeon E5530 and 16GB RAM, and *Local-i5*, which has a quad-core 3.4GHz Intel Core i5-3570 and 8GB RAM. Both machines run 64-bit Ubuntu 12.04.2 LTS. We use them to evaluate the encoding performance of CDStore clients.

(ii) *LAN:* We configure a LAN of multiple machines with the same configuration as *Local-i5*. All nodes are connected via a 1Gb/s switch. We run CDStore clients and servers on different machines. Each CDStore server mounts the storage backend on a local 7200RPM SATA

hard disk. We use the LAN testbed to evaluate the data transfer performance of CDStore.

(iii) *Cloud:* We deploy a CDStore client on the Local-Xeon machine (in Hong Kong) and connect it via the Internet to four commercial clouds (i.e., $n = 4$): Amazon (in Singapore), Google (in Singapore), Azure (in Hong Kong), and Rackspace (in Hong Kong). We set up the testbed in the same continent to limit the differences among the client-to-server connection bandwidths. Each cloud runs a VM with similar configurations: four CPU cores and 4~15GB RAM. We use the cloud testbed to evaluate the real deployment performance of CDStore.

5.2 Datasets

We use two real-world datasets to drive our evaluation.

(i) *FSL:* This dataset is published by the File systems and Storage Lab (FSL) at Stony Brook University [3,57]. Due to the large dataset size, we use the `Fslhomes` dataset in 2013, containing daily snapshots of nine students' home directories from a shared network file system. We select the snapshots every seven days (which are not continuous) to mimic weekly backups. The dataset is represented in 48-bit chunk fingerprints and corresponding chunk sizes obtained from variable-size chunking. Our filtered FSL dataset contains 16 weekly backups of all nine users, covering a total of 8.11TB of data.

(ii) *VM:* This dataset is collected by ourselves and is unpublished. It consists of weekly snapshots of 156 VM images for students in a university programming course in Spring 2014. We create a 10GB master image with Ubuntu 12.04.2 LTS and clone all VMs. We treat each VM image snapshot as a weekly backup of a user. The dataset is represented in SHA-1 fingerprints on 4KB fixed-size chunks. It spans 16 weeks, totaling 24.38TB of data. For fair comparisons, we remove all zero-filled chunks (which dominate in VM images [31]) from the dataset, and the size reduces to 11.12TB.

5.3 Encoding Performance

We evaluate the computational overhead of CAONT-RS when encoding secrets into shares. We compare CAONT-RS with two variants: (i) *AONT-RS* [52], which builds on Rivest's AONT [53] and does not support deduplication, and (ii) our prior proposal *CAONT-RS-Rivest* [37], which uses Rivest's AONT as in AONT-RS and replaces the random key in AONT-RS with a SHA-256 hash for convergent dispersal. CAONT-RS uses OAEP-based AONT instead (see §3.2).

We conduct our experiments on the Local-Xeon and Local-i5 machines. We create 2GB of random data in memory (to remove I/O overhead), generate secrets using variable-size chunking with an average chunk size 8KB, and encode them into shares. We measure the *encoding speed*, defined as the ratio of the original data size to the total time of encoding all secrets into shares. Our results

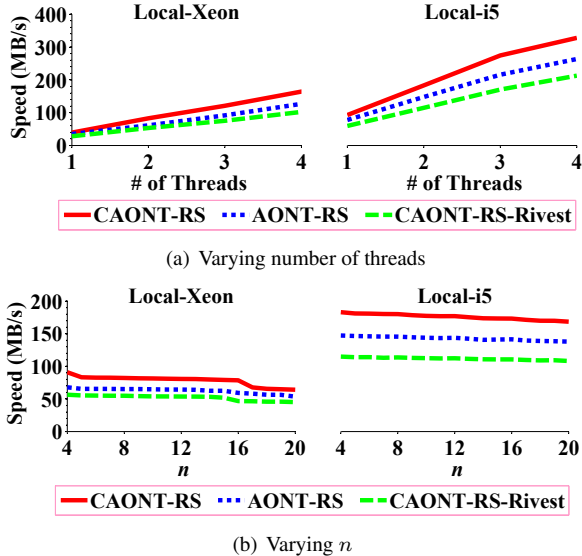


Figure 5: Encoding speeds of a CDStore client.

are averaged over 10 runs. We observe similar results for decoding, and omit them here.

We first examine the benefits of multi-threading (see §4.6). Figure 5(a) shows the encoding speeds versus the number of threads, while we fix $(n, k) = (4, 3)$. The encoding speeds of all schemes increase with the number of threads. If two encoding threads are used, the encoding speeds of CAONT-RS are 83MB/s on Local-Xeon and 183MB/s on Local-i5. Also, OAEP-based AONT in CAONT-RS brings remarkable performance gains. Compared to CAONT-RS-Rivest, which performs encryptions on small words based on Rivest’s AONT, CAONT-RS improves the encoding speed by 40~61% on Local-Xeon and 54~61% on Local-i5; even though compared to AONT-RS, which uses one fewer hash operation, CAONT-RS still increases the encoding speed by 12~35% on Local-Xeon and 19~27% on Local-i5.

We next evaluate the impact of n (number of clouds). We vary n from 4 to 20, and fix two encoding threads. We configure k as the largest integer that satisfies $\frac{k}{n} \leq \frac{3}{4}$ (e.g., $n = 4$ implies $k = 3$), so as to maintain a similar storage blowup due to secret sharing. Figure 5(b) shows the encoding speeds versus n . The encoding speeds of all schemes slightly decrease with n (e.g., by 8% from $n = 4$ to 20 for CAONT-RS on Local-i5), since more encoded shares are generated via Reed-Solomon codes for a larger n . However, Reed-Solomon coding only accounts for small overhead compared to AONT, which runs cryptographic operations. We have also tested other ratios of $\frac{k}{n}$ and obtained similar speed results.

The above results only report encoding speeds, while a CDStore client performs both chunking and encoding operations when uploading data to multiple clouds. We measure the combined chunking (using variable-size

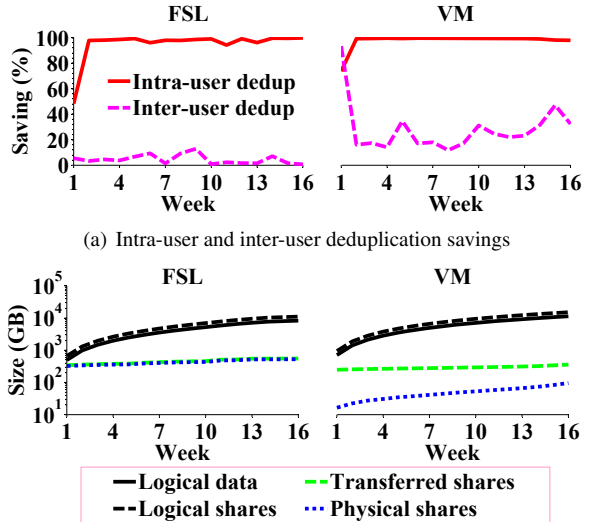


Figure 6: Deduplication efficiency of CDStore.

chunking) and encoding speeds with $(n, k) = (4, 3)$ and two encoding threads, and find that the combined speeds drop by around 16%, to 69MB/s on Local-Xeon and 154MB/s on Local-i5.

5.4 Deduplication Efficiency

We evaluate the effectiveness of both intra-user and inter-user deduplications (see §3.3). We extract the deduplication characteristics of both datasets, assuming that they are stored as weekly backups. We define four types of data: (i) *logical data*, the original user data to be encoded into shares, (ii) *logical shares*, the shares before two-stage deduplication, (iii) *transferred shares*, the shares that are transferred over Internet after intra-user deduplication, and (iv) *physical shares*, the shares that are finally stored after two-stage deduplication. We also define two metrics: (i) *intra-user deduplication saving*, which is one minus the ratio of the size of the transferred shares to that of the logical shares, and (ii) *inter-user deduplication saving*, which is one minus the ratio of the size of the physical shares to that of the transferred shares. We fix $(n, k) = (4, 3)$. Figure 6 summarizes the results.

Figure 6(a) first shows the intra-user and inter-user deduplication savings. The intra-user deduplication savings are very high for both datasets, especially in subsequent backups after the first week (at least 94.2% for FSL and at least 98.0% for VM). The reason is that the users only modify or add a small portion of data. The savings translate to performance gains in file uploads (see §5.5). However, the inter-user deduplication savings differ across datasets. For the FSL dataset, the savings fall to no more than 12.9%. In contrast, for the VM dataset, the saving for the first backup reaches 93.4%, mainly because the VM images are initially installed with the same

operating system. The savings for subsequent backups then drop to the range between 11.8% and 47.0%. Nevertheless, the VM dataset shows higher savings for subsequent backups than the FSL dataset; we conjecture the reason is that students make similar changes to the VM images when doing programming assignments.

Figure 6(b) then shows cumulative data and share sizes before and after intra-user and inter-user deduplications. After 16 weekly backups, for the FSL dataset, the total size of physical shares is only 0.51TB, about 6.3% of the logical data size; for the VM dataset, the total size of physical shares is only 0.09TB, about 0.8% of the logical data size. This shows that dispersal-level redundancy (i.e., $\frac{n}{k} = \frac{4}{3}$) is significantly offset by removing content-level redundancy via two-stage deduplication. Also, if we compare the sizes of transferred shares and physical shares for the VM dataset, we see that inter-user deduplication is crucial for reducing storage space.

5.5 Transfer Speeds

Single-client baseline transfer speeds: We first evaluate the baseline transfer speed of a CDStore client using both LAN and cloud testbeds. Each testbed has one CDStore client and four CDStore servers with $(n, k) = (4, 3)$. We first upload 2GB of unique data (i.e., no duplicates), then upload another 2GB of duplicate data identical to the previous one, and finally download the 2GB data from three CDStore servers (for the cloud testbed, we choose Google, Azure, and Rackspace for downloads). We measure the upload and download speeds, averaged over 10 runs.

Figure 7(a) presents the results. On the LAN testbed, the upload speed for unique data is 77MB/s. Our measurements find that the effective network speed in our LAN testbed is around 110MB/s. Thus, the upload speed for unique data is close to $\frac{k}{n}$ of the effective network speed. Uploading duplicate data has speed 150MB/s. Since it does not transfer actual data after intra-user deduplication, the performance is bounded by the chunking and CAONT-RS encoding operations (see §5.3). The download speed is 99MB/s, about 10% less than the effective network speed. The reason is that the CDStore servers need to retrieve data from the disk backend before returning it to the CDStore client.

On the cloud testbed, the upload and download performance is limited by the Internet bandwidth. For references, we measure the upload and download speeds of each individual cloud when transferring 2GB of unique data divided in 4MB units (see §4.1), and Table 2 presents the averaged results over 10 runs. Since CDStore transfers data through multiple clouds in parallel via multi-threading, its upload speed of unique data and download speed are higher than those of individual clouds (e.g., Amazon and Google). The upload speed for unique data is smaller than the download speed because

Cloud	Upload speed	Download speed
Amazon	5.87 (0.19)	4.45 (0.30)
Google	4.99 (0.23)	4.45 (0.21)
Azure	19.59 (1.20)	13.78 (0.72)
Rackspace	19.42 (1.06)	12.93 (1.47)

Table 2: Measured speeds (MB/s) of each of four clouds, in terms of the average (standard deviation) over 10 runs.

of sending redundancy and connecting to more clouds. The upload speed for duplicate data is over $9\times$ that for unique data, and this difference is more significant than on the LAN testbed.

Single-client trace-driven transfer speeds: We now evaluate the upload and download speeds of a single CDStore client using datasets as opposed to unique and duplicate data above. We focus on the FSL dataset, which allows us to test the effect of variable-size chunking. We again consider both LAN and cloud testbeds with $(n, k) = (4, 3)$. Since the FSL dataset only has chunk fingerprints and chunk sizes, we reconstruct a chunk by writing the fingerprint value repeatedly to a chunk with the specified size, so as to preserve content similarity. Each chunk is treated as a secret, which will be encoded into shares. We first upload all backups to CDStore servers, followed by downloading them. To reduce evaluation time, we only run part of the dataset. On the LAN testbed, we run seven weekly backups for five users (1.06TB data in total). We feed the first week of backups of each user one by one through the CDStore client, followed by the second week of backups, and so on. On the other hand, on the cloud testbed, we run two weekly backups for a single user (21.35GB data in total).

Figure 7(b) presents three results: (i) the average upload speed for the first backup (averaged over five users for the LAN testbed), (ii) the average upload speed for the subsequent backups, and (iii) the average download speed of all backups. The presented results are obtained from a single run, yet the evaluation time is long enough to give steady-state results. We compare the results with those for unique and duplicate data in Figure 7(a).

We see that the upload speed for the first backup exceeds that for unique data (e.g., by 19% on the LAN testbed), mainly because the first backup contains duplicates, which can be removed by intra-user deduplication (see Figure 6(a)). The upload speed for the subsequent backups approximates to that for duplicate data, as most duplicates are again removed by intra-user deduplication.

The trace-driven download speed is lower than the baseline one in Figure 7(a) (e.g., by 10% on the LAN testbed), since deduplication now introduces chunk fragmentation [38] for subsequent backups. Nevertheless, we find that the variance of the download speeds of the backups is very small (not shown in the figure), although

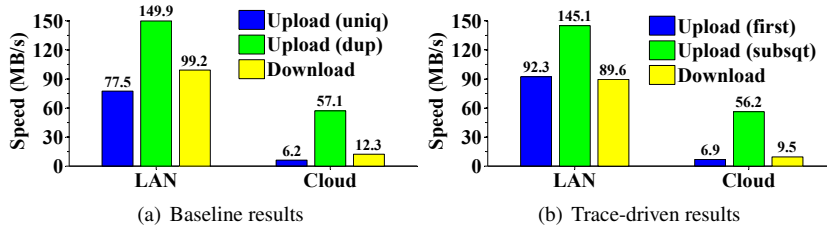


Figure 7: Upload and download speeds of a CDStore client (the numbers are the speeds in MB/s).

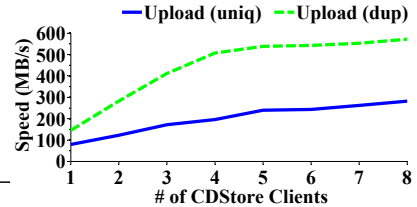


Figure 8: Aggregate upload speeds of multiple CDStore clients.

the number of accessed containers increases for subsequent backups. The download speed will gradually degrade due to fragmentation as we store more backups. We do not explicitly address fragmentation in this work.

Multi-client aggregate upload speeds: We evaluate the aggregate upload speed when multiple CDStore clients connect to multiple CDStore servers. We mainly consider data uploads on the LAN testbed, in which we vary the number of CDStore clients, each hosted on a dedicated machine, and configure four CDStore servers with $(n, k) = (4, 3)$. All CDStore clients perform uploads concurrently, such that each of them first uploads 2GB of unique data, and then uploads another 2GB of duplicate data. We measure the *aggregate upload speed*, defined as the total upload size (i.e., 2GB times the number of clients) divided by the duration when all clients finish uploads. Our results are averaged over 10 runs.

Figure 8 presents the aggregate upload speeds for both unique and duplicate data, which we observe increase with the number of CDStore clients. For unique data, the aggregate upload speed reaches 282MB/s for eight CDStore clients. The speed is limited by the network bandwidth and disk I/O, where the latter is for the CDStore servers to write containers to disk. If we exclude disk I/O (i.e., without writing data), the aggregate upload speed can reach 310MB/s (not shown in the figure), which approximates to the aggregate effective Ethernet speed of $k = 3$ CDStore servers. For duplicate data, there is no actual data transfer, so the aggregate upload speed can reach 572MB/s. Note that the knee point at four CDStore clients is due to the saturation of CPU resources in each CDStore server.

5.6 Cost Analysis

We now analyze the cost saving of CDStore. We compare it with two baseline systems: (i) an AONT-RS-based multi-cloud system that has the same levels of reliability and security as CDStore but does not support deduplication, and (ii) a single-cloud system that incurs zero redundancy for reliability, but encrypts user data with random keys and does not support deduplication. We aim to show that CDStore incurs less cost than AONT-RS through deduplication; even though CDStore incurs redundancy for reliability, it still incurs less cost than the

single-cloud system without deduplication.

We develop a tool to estimate the monetary costs using the pricing models of Amazon EC2 [1] and S3 [2] in September 2014. Free charges apply to data transfers between co-locating EC2 instances and S3 storage, and also inbound transfers to both EC2 and S3. We only study backup operations, and do not consider restore operations as they are relatively infrequent in practice. Note that both EC2 and S3 follow tiered pricing, so the exact charges depend on the actual usage. Our tool takes into account tiered pricing in cost calculations. For CDStore, we also consider the storage costs of file recipes.

We briefly describe how we derive the EC2 and S3 costs. For EC2, we consider the category of high-utilization reserved instances, which are priced based on an upfront fee and hourly bills. We focus on two types of instances, namely compute-optimized and storage-optimized, to host CDStore servers on all clouds. Each instance charges around US\$60~1,300 per month, depending on the CPU, memory, and storage settings. Note that both file and share indices (see §4.4) are kept in the local storage of an EC2 instance, and the total index size is determined by how much data is stored and how much data can be deduplicated. Our tool chooses the cheapest instance that can keep the entire indices according to the storage size and deduplication efficiency, both of which can be estimated in practice. On the other hand, S3 storage is mainly priced based on storage size, and it charges around US\$30 per TB per month. Note that in backup operations, the costs due to outbound transfer (e.g., a CDStore server replies the intra-user deduplication status to a CDStore client) and storage requests (e.g., PUT) are negligible compared to VM and storage costs.

We consider a case study. An organization schedules weekly backups for its user data, for a retention time of half a year (26 weeks). We fix $(n, k) = (4, 3)$ (i.e., we host four EC2 instances for CDStore servers). We vary the weekly backup size and the deduplication ratio, where the latter is defined as the ratio of the size of logical shares to the size of physical shares (see §5.4).

Figure 9(a) shows the cost savings of CDStore versus different weekly backup sizes, while we fix the deduplication ratio as $10\times$ [58]. The cost savings increase with the weekly backup size. For example, if we

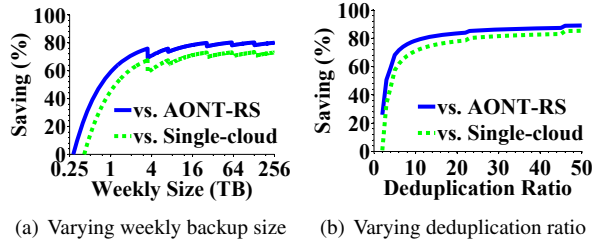


Figure 9: Cost savings of CDStore over an AONT-RS-based multi-cloud system and a single-cloud system.

keep a weekly backup size of 16TB, the single-cloud and AONT-RS-based systems incur total storage costs (with tiered pricing) of around US\$12,250/month and US\$16,400/month, respectively; CDStore incurs additional VM costs of around US\$660/month but reduces the storage cost to around US\$2,880/month, resulting in around US\$3,540/month in total and thus achieving at least 70% of cost savings as a whole. The cost saving of CDStore over AONT-RS is higher than that over a single cloud, as the former introduces dispersal-level redundancy for fault tolerance. The increase slows down as the weekly backup size further increases, since the overhead of file recipes becomes significant when the total backup size is large while the backups have a high deduplication ratio [41]. Note that the jagged curves are due to the switch of the cheapest EC2 instance to fit the indices.

Figure 9(b) shows the cost savings of CDStore versus different deduplication ratios, where the weekly backup size is fixed at 16TB. The cost saving increases with the deduplication ratio. The saving is about 70~80% when the deduplication ratio is between 10 \times and 50 \times .

6 Related Work

Multi-cloud storage: Existing multi-cloud storage systems mainly focus on data availability in the presence of cloud failures and vendor lock-ins. For example, SafeStore [33], RACS [5], Scalia [45], and NCCloud [29] disperse redundancy across multiple clouds using RAID or erasure coding. Some multi-cloud systems additionally address security. HAIL [19] proposes proof of retrievability to support remote integrity checking against data corruptions. MetaStorage [12] and SPANStore [60] provide both availability and integrity guarantees by replicating data across multiple clouds using quorum techniques [39], but do not address confidentiality. Hybris [23] achieves confidentiality by dispersing encrypted data over multiple public clouds via erasure coding and keeping secret keys in a private cloud.

Applications of secret sharing: We discuss several secret sharing algorithms in §2. They have been realized by storage systems. POTSHARDS [56] realizes Shamir’s scheme [54] for archival storage. ICStore [21] achieves confidentiality via key-based encryption,

where the keys are distributed across multiple clouds via Shamir’s scheme. DepSky [13] and SCFS [14] distribute keys across clouds using SSMS [34]. Cleversafe [52] uses AONT-RS to achieve security with reduced storage space. All the above systems rely on random inputs to secret sharing, and do not address deduplication.

Deduplication security: Convergent encryption [24] provides confidentiality guarantees for deduplication storage, and has been adopted in various storage systems [6, 7, 22, 55, 59]. However, the key management overheads of convergent encryption are significant [36]. Bellare *et al.* [10] generalize convergent encryption into Message-locked encryption (MLE) and provide formal security analysis on confidentiality and tag consistency. The same authors also prototype a server-aided MLE system DupLESS [9], which uses more complicated encryption keys to prevent brute-force attacks. DupLESS maintains the keys in a dedicated key server, yet the key server is a single point of failure.

Client-side inter-user deduplication poses new security threats, including the side-channel attack [27,28] and some specific attacks against Dropbox [43]. CDStore addresses this problem through two-stage deduplication. A previous work [61] proposes a similar two-stage deduplication approach (i.e., inner-VM and cross-VM deduplications) to reduce system resources for VM backups, while our approach is mainly to address security.

7 Conclusions

We propose a multi-cloud storage system called CDStore for organizations to outsource backup and archival storage to public cloud vendors, with three goals in mind: reliability, security, and cost efficiency. The core design of CDStore is convergent dispersal, which augments secret sharing with the deduplication capability. CDStore also adopts two-stage deduplication to achieve bandwidth and storage savings and prevent side-channel attacks. We extensively evaluate CDStore via different testbeds and datasets from both performance and cost perspectives. We demonstrate that deduplication enables CDStore to achieve cost savings. The source code of our CDStore prototype is available at <http://ansrlab.cse.cuhk.edu.hk/software/cdstore>.

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References

- [1] Amazon EC2. <http://aws.amazon.com/ec2/>, 2014.

- [2] Amazon S3. <http://aws.amazon.com/s3/>, 2014.
- [3] FSL traces and snapshots public archive. <http://tracer.filesystems.org/>, 2014.
- [4] OpenSSL Project. <http://www.openssl.org>, 2014.
- [5] H. Abu-Libdeh, L. Princehouse, and H. Weatherpoon. RACS: A case for cloud storage diversity. In *Proceedings of the 1st ACM Symposium on Cloud Computing (SoCC '10)*, pages 229–240, Indianapolis, IN, June 2010.
- [6] A. Adya, W. J. Bolosky, M. Castro, G. Cermak, R. Chaiken, J. R. Douceur, J. Howell, J. R. Lorch, M. Theimer, and R. P. Wattenhofer. FARSITE: Federated, available, and reliable storage for an incompletely trusted environment. In *Proceedings of the 5th Symposium on Operating Systems Design and Implementation (OSDI '02)*, pages 1–14, Boston, MA, Dec. 2002.
- [7] P. Anderson and L. Zhang. Fast and secure laptop backups with encrypted de-duplication. In *Proceedings of the 24th Large Installation System Administration Conference (LISA '10)*, pages 1–12, San Jose, CA, Nov. 2010.
- [8] M. Armbrust, A. Fox, R. Griffith, A. D. Joseph, R. Katz, A. Konwinski, G. Lee, D. Patterson, A. Rabkin, I. Stoica, and M. Zaha. A view of cloud computing. *Communications of the ACM*, 53(4):50–58, Apr. 2010.
- [9] M. Bellare, S. Keelveedhi, and T. Ristenpart. DupLESS: Server-aided encryption for deduplicated storage. In *Proceedings of the 22nd USENIX Security Symposium (Security '13)*, pages 179–194, Washington, DC, Aug. 2013.
- [10] M. Bellare, S. Keelveedhi, and T. Ristenpart. Message-locked encryption and secure deduplication. In *Proceedings of the 32nd Annual International Conference on the Theory and Applications of Cryptographic Techniques (EUROCRYPT '13)*, pages 296–312, Athens, Greece, May 2013.
- [11] M. Bellare and P. Rogaway. Optimal asymmetric encryption. In *Proceedings of the 1994 Workshop on the Theory and Application of Cryptographic Techniques (EUROCRYPT '94)*, pages 92–111, Perugia, Italy, May 1994.
- [12] D. Bermbach, M. Klems, S. Tai, and M. Menzel. MetaStorage: A federated cloud storage system to manage consistency-latency tradeoffs. In *Proceedings of the 2011 IEEE 4th International Conference on Cloud Computing (CLOUD '11)*, pages 452–459, Washington, DC, July 2011.
- [13] A. Bessani, M. Correia, B. Quaresma, F. André, and P. Sousa. DepSky: Dependable and secure storage in a cloud-of-clouds. *ACM Transactions on Storage*, 9(4):1–33, Nov. 2013.
- [14] A. Bessani, R. Mendes, T. Oliveira, N. Neves, M. Correia, M. Pasin, and P. Verissimo. SCFS: A shared cloud-backed file system. In *Proceedings of the 2014 USENIX Annual Technical Conference (ATC '14)*, pages 169–180, Philadelphia, PA, June 2014.
- [15] J. Black. Compare-by-hash: A reasoned analysis. In *Proceedings of the 2006 USENIX Annual Technical Conference (ATC'06)*, pages 85–90, Boston, MA, June 2006.
- [16] G. R. Blakley and C. Meadows. Security of ramp schemes. In *Proceedings of CRYPTO '84 on Advances in Cryptology*, pages 242–268, Santa Barbara, CA, Aug 1984.
- [17] J. Blomer, M. Kalfane, R. Karp, M. Karpinski, M. Luby, and D. Zuckerman. An XOR-based erasure-resilient coding scheme. Technical Report TR-95-048, International Computer Science Institute, UC Berkeley, Aug. 1995.
- [18] B. H. Bloom. Space/time trade-offs in hash coding with allowable errors. *Communications of the ACM*, 13(7):422–426, July 1970.
- [19] K. D. Bowers, A. Juels, and A. Oprea. HAIL: A high-availability and integrity layer for cloud storage. In *Proceedings of 16th ACM Conference on Computer and Communications Security (CCS '09)*, pages 187–198, Chicago, IL, Nov. 2009.
- [20] V. Boyko. On the security properties of OAEP as an all-or-nothing transform. In *Proceedings of the 19th Annual International Cryptology Conference (CRYPTO '99)*, pages 503–518, Santa Barbara, CA, Aug. 1999.
- [21] C. Cachin, R. Haas, and M. Vukolić. Dependable storage in the intercloud. IBM Research Report RZ 3783, May 2010.
- [22] L. P. Cox, C. D. Murray, and B. D. Noble. Pastiche: Making backup cheap and easy. In *Proceedings of the 5th Symposium on Operating Systems Design and Implementation (OSDI '02)*, pages 1–14, Boston, MA, Dec. 2002.
- [23] D. Dobre, P. Viotti, and M. Vukolić. Hybris: Robust hybrid cloud storage. In *Proceedings of the 2014 ACM Symposium on Cloud Computing (SoCC'14)*, pages 1–14, Seattle, WA, Nov. 2014.
- [24] J. R. Douceur, A. Adya, W. J. Bolosky, D. Simon, and M. Theimer. Reclaiming space from duplicate

- files in a serverless distributed file system. In *Proceedings of the 22nd International Conference on Distributed Computing Systems (ICDCS'02)*, pages 617–624, Vienna, Austria, July 2002.
- [25] M. Fu, D. Feng, Y. Hua, X. He, Z. Chen, W. Xia, F. Huang, and Q. Liu. Accelerating restore and garbage collection in deduplication-based backup systems via exploiting historical information. In *Proceedings of the 2014 USENIX Annual Technical Conference (ATC '14)*, pages 181–192, Philadelphia, PA, June 2014.
- [26] S. Ghemawat and J. Dean. LevelDB: A fast and lightweight key/value database library by Google. <http://code.google.com/p/leveldb/>, 2014.
- [27] S. Halevi, D. Harnik, B. Pinkas, and A. Shulman-Peleg. Proofs of ownership in remote storage systems. In *Proceedings of the 18th ACM Conference on Computer and Communications Security (CCS '11)*, pages 491–500, Chicago, IL, Oct. 2011.
- [28] D. Harnik, B. Pinkas, and A. Shulman-Peleg. Side channels in cloud services: Deduplication in cloud storage. *IEEE Security & Privacy*, 8(6):40–47, Nov-Dec 2010.
- [29] Y. Hu, H. C. H. Chen, P. P. C. Lee, and Y. Tang. NCCloud: Applying network coding for the storage repair in a cloud-of-clouds. In *Proceedings of the 10th USENIX Conference on File and Storage Technologies (FAST '12)*, pages 265–272, San Jose, CA, Feb. 2012.
- [30] R. Jelinek, Y. Zhai, T. Ristenpart, and M. Swift. A day late and a dollar short: The case for research on cloud billing systems. In *Proceedings of the 6th USENIX Workshop on Hot Topics in Cloud Computing (HotCloud '14)*, pages 1–6, Philadelphia, PA, June 2014.
- [31] K. Jin and E. L. Miller. The effectiveness of deduplication on virtual machine disk images. In *Proceedings of the 2009 Israeli Experimental Systems Conference (SYSTOR '09)*, pages 1–12, Haifa, Israel, May 2009.
- [32] M. Kaczmarczyk, M. Barczynski, W. Kilian, and C. Dubnicki. Reducing impact of data fragmentation caused by in-line deduplication. In *Proceedings of the 5th Annual International Systems and Storage Conference (SYSTOR '12)*, pages 1–12, Haifa, Israel, June 2012.
- [33] R. Kotla, L. Alvisi, and M. Dahlin. SafeStore: A durable and practical storage system. In *Proceedings of the 2007 USENIX Annual Technical Conference (ATC '07)*, pages 129–142, Santa Clara, CA, June 2007.
- [34] H. Krawczyk. Secret sharing made short. In *Proceedings of the 13th Annual International Cryptology Conference on Advances in Cryptology (CRYPTO '93)*, pages 136–146, Santa Barbara, CA, Aug. 1993.
- [35] S. Lelii. Nirvanix prepares to close, tells customers to stop using its cloud. <http://itknowledgeexchange.techtarget.com/storage-soup/nirvanix-to-customers-stop-sending-data-to-our-cloud/>, Sept. 2013.
- [36] J. Li, X. Chen, M. Li, J. Li, P. P. C. Lee, and W. Lou. Secure deduplication with efficient and reliable convergent key management. *IEEE Transactions on Parallel and Distributed Systems*, 25(6):1615–1625, June 2014.
- [37] M. Li, C. Qin, P. P. C. Lee, and J. Li. Convergent dispersal: Toward storage-efficient security in a cloud-of-clouds. In *Proceedings of the 6th USENIX Workshop on Hot Topics in Storage and File Systems (HotStorage '14)*, pages 1–5, Philadelphia, PA, June 2014.
- [38] M. Lillibridge, K. Eshghi, and D. Bhagwat. Improving restore speed for backup systems that use inline chunk-based deduplication. In *Proceedings of the 11th USENIX Conference on File and Storage Technologies (FAST '13)*, pages 183–197, San Jose, CA, Feb. 2013.
- [39] D. Malkhi and M. Reiter. Byzantine quorum systems. In *Proceedings of the 29th Annual ACM Symposium on the Theory of Computing (STOC '97)*, pages 569–578, El Paso, TX, May 1997.
- [40] C. McLellan. Storage in 2014: An overview. <http://www.zdnet.com/storage-in-2014-an-overview-7000024712/>, Jan. 2014.
- [41] D. Meister, A. Brinkmann, and T. Süß. File recipe compression in data deduplication systems. In *Proceedings of the 11th USENIX conference on File and Storage Technologies (FAST '13)*, pages 175–182, San Jose, CA, Feb. 2013.
- [42] D. T. Meyer and W. J. Bolosky. A study of practical deduplication. In *Proceedings of the 9th USENIX Conference on File and Storage Technologies (FAST '11)*, pages 1–14, San Jose, CA, Feb. 2011.
- [43] M. Mulazzani, S. Schrittwieser, M. Leithner, M. Huber, and E. Weippl. Dark clouds on the horizon: Using cloud storage as attack vector and online slack space. In *Proceedings of the 20th USENIX Security Symposium (Security '11)*, pages 65–76, San Francisco, CA, Aug. 2011.

- [44] P. O’Neil, E. Cheng, D. Gawlick, and E. O’Neil. The log-structured merge-tree (LSM-tree). *Acta Informatica*, 33(4):351–385, June 1996.
- [45] T. G. Papaioannou, N. Bonvin, and K. Aberer. Scalia: An adaptive scheme for efficient multi-cloud storage. In *Proceedings of the 2012 International Conference for High Performance Computing, Networking, Storage and Analysis (SC ’12)*, pages 1–10, Salt Lake City, UT, Nov. 2012.
- [46] J. S. Plank. A tutorial on Reed-Solomon coding for fault-tolerance in RAID-like systems. *Software — Practice & Experience*, 27(9):995–1012, Sept. 1997.
- [47] J. S. Plank and Y. Ding. Note: Correction to the 1997 tutorial on Reed-Solomon coding. *Software — Practice & Experience*, 35(2):189–194, Feb. 2005.
- [48] J. S. Plank, K. M. Greenan, and E. L. Miller. Screaming fast Galois Field arithmetic using Intel SIMD instructions. In *Proceedings of the 11th USENIX conference on File and Storage Technologies (FAST ’13)*, pages 299–306, San Jose, CA, Feb. 2013.
- [49] M. Rabin. Fingerprint by random polynomials. Technical report, Technical Report TR-15-81, Center for Research in Computing Technology, Harvard University, 1981.
- [50] M. Rabin. Efficient dispersal of information for security, load balancing, and fault tolerance. *Journal of the ACM*, 36(2):335–348, Apr. 1989.
- [51] I. S. Reed and G. Solomon. Polynomial codes over certain finite fields. *Journal of the Society for Industrial and Applied Mathematics*, 8(2):300–304, June 1960.
- [52] J. K. Resch and J. S. Plank. AONT-RS: Blending security and performance in dispersed storage systems. In *Proceedings of the 9th USENIX Conference on File and Storage Technologies (FAST ’11)*, pages 191–202, San Jose, CA, Feb. 2011.
- [53] R. L. Rivest. All-or-nothing encryption and the package transform. In *Proceedings of the 4th International Workshop on Fast Software Encryption (FSE ’97)*, pages 210–218, Haifa, Israel, Jan. 1997.
- [54] A. Shamir. How to share a secret. *Communications of the ACM*, 22(11):612–613, Nov. 1979.
- [55] M. W. Storer, K. Greenan, D. D. E. Long, and E. L. Miller. Secure data deduplication. In *Proceedings of the 4th ACM International Workshop on Storage Security and Survivability (StorageSS ’08)*, pages 1–10, Fairfax, VA, Oct. 2008.
- [56] M. W. Storer, K. M. Greenan, E. L. Miller, and K. Voruganti. POTSHARDS — a secure, recoverable, long-term archival storage system. *ACM Transactions on Storage*, 5(2):1–35, June 2009.
- [57] V. Tarasov, A. Mudrankit, W. Buik, P. Shilane, G. Kuenning, and E. Zadok. Generating realistic datasets for deduplication analysis. In *Proceedings of the 2012 USENIX Annual Technical Conference (ATC ’12)*, pages 261–272, Boston, MA, June 2012.
- [58] G. Wallace, F. Douglass, H. Qian, P. Shilane, S. Smaldone, M. Chamness, and W. Hsu. Characteristics of backup workloads in production systems. In *Proceedings of the 10th USENIX Conference on File and Storage Technologies (FAST ’12)*, pages 33–48, San Jose, CA, Feb. 2012.
- [59] Z. Wilcox-O’Hearn and B. Warner. Tahoe — the least-authority filesystem. In *Proceedings of the 4th ACM International Workshop on Storage Security and Survivability (StorageSS ’08)*, pages 21–26, Fairfax, VA, Oct. 2008.
- [60] Z. Wu, M. Butkiewicz, D. Perkins, E. Katz-Bassett, and H. V. Madhyastha. SPANStore: Cost-effective geo-replicated storage spanning multiple cloud services. In *Proceedings of the 24th ACM Symposium on Operating Systems Principles (SOSP ’13)*, pages 292–308, Farmington, PA, Nov. 2013.
- [61] W. Zhang, H. Tang, H. Jiang, T. Yang, X. Li, and Y. Zeng. Multi-level selective deduplication for VM snapshots in cloud storage. In *Proceedings of the 2012 IEEE 5th International Conference on Cloud Computing (CLOUD ’12)*, pages 550–557, Honolulu, HI, June 2012.
- [62] B. Zhu, K. Li, and H. Patterson. Avoiding the disk bottleneck in the data domain deduplication file system. In *Proceedings of the 6th USENIX Conference on File and Storage Technologies (FAST ’08)*, pages 269–282, San Jose, CA, Feb. 2008.