CAOS: Concurrent-Access Obfuscated Store

Mihai Ordean  
University of Birmingham, UK  
m.ordean@cs.bham.ac.uk

Mark Ryan  
University of Birmingham, UK  
m.d.ryan@cs.bham.ac.uk

David Galindo  
University of Birmingham and Fetch.AI, Cambridge, UK  
d.galindo@cs.bham.ac.uk

ABSTRACT
This paper proposes Concurrent-Access Obfuscated Store (CAOS), a construction for remote data storage that provides access-pattern obfuscation in a honest-but-curious adversarial model, while allowing for low bandwidth overhead and client storage. Compared to other approaches, the main advantage of CAOS is that it supports concurrent access without a proxy, for multiple read-only clients and a single read-write client. Concurrent access is achieved by letting clients maintain independent maps that describe how the data is stored. Even though the maps might diverge from client to client, the protocol guarantees that clients will always have access to the data. Efficiency and concurrency are achieved at the expense of perfect obfuscation: in CAOS the extent to which access patterns are hidden is determined by the resources allocated to its built-in obfuscation mechanism. To assess this trade-off we provide both a security and a performance analysis of CAOS. We additionally provide a proof-of-concept implementation1.

CCS CONCEPTS
- Security and privacy → Management and querying of encrypted data; File system security;

KEYWORDS
data obfuscation; concurrent-access obfuscated store; access pattern

1 INTRODUCTION
Cloud computing has become an attractive solution for data storage. Unfortunately, current cloud computing architectures do not provide sufficient and reliable security for private and sensitive data. Even when encryption is used, malicious servers and operators can learn user access patterns and derive information based on them (e.g., data accessed more often can be assumed to be more important) [7].

One cryptographic primitive specifically designed to hide access patterns is Oblivious RAM (ORAM). This primitive was introduced by Goldreich and Ostrovsky [12, 13] for the purposes of preventing software reverse engineering by hiding a program’s access patterns to memory. The issue has since become important in the context of cloud computing, where clients and data-store servers often reside in different trust domains and trust between them cannot always be established. Modern ORAM schemes [10, 16, 22] are seen as viable options of addressing this problem. However, in real-life scenarios, even the best ORAMs can prove to be impractical [15], mainly because of the high bandwidth requirements and/or client storage constraints. Another major limitation of modern ORAM constructions is that they are mainly restricted to having a single-client that connects to the data-store server. This is because data in the store is accessed through a client maintained local structure (i.e. a map). Migrating from this model has proven difficult. Even small deviations [20, 23], such as allowing multiple clients to access the store through a proxy that acts as the single-client have been shown to have vulnerabilities [17].

As ORAMs have been difficult to use in real-life, other specialised, and more efficient security primitives have been developed in the context of privacy preserving access to cloud-stored data e.g. searchable encryption (SE) schemes. SE uses either symmetric keys [8, 9, 18] or public keys [19] and allows clients to securely search cloud stored databases through precomputed ciphertexts called trapdoors. SE schemes have low computational requirements from clients and are bandwidth efficient. However, prior work has shown that searchable encryption schemes leak significant amounts of information about their encrypted indexes when using attacks which combine access-pattern analysis, background information about data stored, and language-based word frequency knowledge [14]. Incorporating changes and updates to the searched database is also a difficult process. Often schemes require the whole index to be regenerated for any the new information added [8, 9]. Finally, SE schemes are restricted to search operations, actual data retrieval needs to happen through a private information retrieval protocol [6] or an ORAM.

As such, an ideal system would have the general applicability and access-pattern privacy of ORAM (cloud storage which hides access patterns), and bandwidth efficiency and concurrent access capabilities similar to those of SE schemes. In this paper we take steps towards this direction by proposing a new design for a general-purpose secure storage with concurrency and bandwidth efficiency. However, the privacy guarantees we provide are not absolute. Instead, our protocol requires that users provision resources for access-pattern obfuscation, and the security guarantees depend on how much of these resources are available.

1.1 Contributions
This paper proposes Concurrent-Access Obfuscated Store (CAOS), a storage access protocol that can hide data access frequency and access patterns, while allowing for concurrent data access. Our main focus when designing CAOS is to obtain a bandwidth-efficient protocol that supports concurrency by design and that is able to provide a customizable amount of data and access-pattern privacy. Our main contributions are as follows:

(1) **Obfuscated access patterns.** We propose a secure access protocol for remote data storage which is able to hide access patterns. Our construction requires at least one of each of the following two types of clients: a *regular client* which stores data, and an *obfuscation client* which hides client’s access patterns. Maximum privacy is achieved as long as at least one obfuscation client behaves honestly.

---

1Available: https://github.com/meehien/caos
(2) **Concurrent access.** We provide, to our knowledge, the first concurrent-access protocol with access-pattern hiding properties that does not require a trusted third party (e.g. proxy). Our concurrent access protocol is applicable in scenarios with multiple readers, but can cope with having a single writer.

(3) **Small and constant bandwidth.** For all clients with read-write/read-only access, our protocol requires a constant bandwidth that is independent of the size of the store. This is possible because we separate the regular access clients and the security responsible clients (i.e. the obfuscation clients). The bandwidth requirements for interacting with the store are also small. In our current instantiation a single block of data requires a constant two blocks to be transferred.

(4) **Security and performance analysis.** We give a game-based definition of data and access-pattern privacy for CAOS-like protocols against honest-but-curious storage servers. Furthermore, we apply this new definition to CAOS and prove it secure. Last but not least we report on the theoretical and observed performance of our protocol thanks to our proof-of-concept implementation.

2 CONCURRENT-ACCESS OBFUSCATED STORE (CAOS)

CAOS is a protocol for storing data securely by encrypting it and anonymizing (read or write) access patterns. CAOS allows users to trade storage space and security for concurrency and bandwidth efficiency.

*Data elements.* In CAOS data is partitioned into blocks of equal size. Each block of data is uniquely identified by a client using a block id (bid). Storing a block remotely involves encrypting the contents of the block and then placing the resulting ciphertext at a random location in the store’s memory. We refer to these locations at the store’s memory as positions. The size of the store is measured in the number of positions it has available for storing blocks. Clients can store the same block at multiple positions and keep track of where their data is located by maintaining a map which links block ids to positions.

*Clients.* There are two types of clients in CAOS: regular clients (RC), which may be read-write (RW) or read-only (RO); and obfuscation clients (OC). Both RC and OC access the store directly and independently from each other.

Regular clients are the main users of the store. They have low bandwidth and local storage requirements, as they only have to store a map. However, accesses done by these clients do leak information about access patterns. Obfuscation clients are the clients that provide security. These clients are able to provide access-pattern obfuscation for themselves as well as RCs. For that purpose OCs use of a buffer which is stored locally in addition to a map. The size of the OC’s local buffer and the OC’s bandwidth requirements are proportional to the speed of obfuscation.

*Access-pattern obfuscation.* Our definitions derive from existing access-pattern security definitions in ORAM [21]. Intuitively, the ORAM definitions require that no information should leak with regards to: (1) which data is being accessed, (2) the frequency of accesses, (3) the relation between accesses, (4) whether access is read or write, and (5) the age of the data. ORAM constructions maintain invariants to ensure that no information is leaked regardless of how many times the store is accessed. CAOS maintains the requirement that no information is leaked for cases (1)-(5), but does not provide guarantees for each individual access operation. Instead, CAOS provides security guarantees for access sequences that involve both regular clients and obfuscation clients. Our security definitions for content and access-pattern security in CAOS are detailed in Section 5.

*Concurrency.* CAOS allows multiple clients to access the store simultaneously and independently from each other. Achieving concurrency in CAOS is not a trivial task. This is because each client’s access operation randomly changes the contents of store, and these changes are only stored locally to that client. Thus, CAOS needs to address two problems: (1) to synchronize locally stored client maps in an efficient manner, and (2) how to allow multiple clients to change the store simultaneously and in a way that does not result in data loss for other clients.

*Syntax.* In the following we draw on the above and give the syntax of our CAOS protocol. Alternative variants of CAOS are possible if adhering to this syntax. We say that an \((n, N)\) store \(S\) is a collection of \(n\) data blocks written to \(N\) store positions such that \(n < N\).

**Definition 2.1.** CAOS consists of a tuple of five PT algorithms \(O = (KGen, INIT, STORE, INIT, OC, ACCESSRW, ACCESSOC)\) over an \((n, N)\) store \(S\):

\[
\begin{align*}
&k \leftarrow KGen(\lambda) : \text{is a setup probabilistic algorithm run by the RW client. It takes as input the security parameter } \lambda \text{ and outputs a secret key } k, \\
&S \leftarrow INIT. STORE(\mathcal{DB}, n, k) : \text{is a deterministic algorithm run by the RW client to initialize the data store. It takes as input a database } \mathcal{DB} = (B_0, \ldots , B_{n−1}) \text{ of } n \text{ data blocks, encrypts each block under key } k, \text{ and distributes them between the total number } N \text{ of store positions}, \\
&buf, S \leftarrow INIT. OC(S, k) : \text{is a deterministic algorithm run by the OC to initialize itself. It requires access to an initialized store } S \text{ and its encryption key } k \text{ and creates the internal buffer of the obfuscation client}, \\
&ret, S \leftarrow ACCESSRW(B, op, d, S, k) : \text{is a probabilistic algorithm that RCs run to access a store. It takes as input the bid } B \text{ to be accessed, the operation } op \in \{\text{read, write}\}, \text{ the data } d \text{ to be written if } op = \text{write}, \text{ and the store } S \text{ and its key } k, \\
&buf, S \leftarrow ACCESSOC(buf, S, k) : \text{is a probabilistic algorithm run by the OC to access a store. It takes as input a local data structure } buf \text{ that acts as a buffer, a store } S \text{ and a key } k. \text{ The algorithm alters the OC’s buffer of the obfuscation client. Additionally, when the obfuscation client runs this algorithm, some positions in the store are read, while others are written. This changes the mapping between blocks and positions.}
\end{align*}
\]
can create redundancies through re-encrypting and ACCESSRW (RCs) to access the same data from multiple store positions we are This is a weaker security guarantee than that used in other works.

This section describes CAOS. We begin with an overview of the

3 EFFICIENT ACCESS-PATTERN OBFUSCATION IN CAOS

This section describes CAOS. We begin with an overview of the protocol and we will follow up with details about the corresponding algorithms and discussing a proof of concept implementation. The complete source-code is available at [1].

3.1 Overview

Access pattern obfuscation. In CAOS we achieve access-pattern obfuscation for sequences of access operations (see Section 5). This is a weaker security guarantee than that used in other works [12, 13, 21], where obfuscation is achieved for each single access operation. In return, our construction allows for concurrence and is more practical.

In CAOS hiding the type of access (read or write) and the age of the data is done by joining both the read and the write operations into a single access function, ACCESSRW. This prevents the adversary from learning when data is read or written, and when new data is added to the store, with the exception of the initial provisioning of the store done by running INIT.STORE.

CAOS uses a locally stored map per client to keep track of which store positions contain which blocks. By setting the size of the store to be larger than the size of the data to be secured, the algorithm ACCESSRW can create redundancies through re-encrypting and duplicating blocks from the store and assign them to random free-positions. We use the term free-positions to refer both to store positions which have never been written, and to positions whose corresponding blocks have at least one redundancy (i.e. blocks that are stored in two or more places). By allowing regular clients (RCs) to access the same data from multiple store positions we are able to partially obfuscate details about the frequency with which specific data is being accessed, and about the relationship between subsequent accesses. We say partially because, even though data is duplicated to random positions, the adversary can still connect these positions to the initial position from where the duplication process began. To address this issue we use obfuscation clients (OCs). These are read-only clients that use the ACCESSSOC function to access the store similarly to RCs. The difference is that OCs maintain a local buffer which is used to store the contents of the positions received from the store. When an OC performs a store access, it writes (i.e. duplicates) in the store a block read from its buffer. As such, blocks that are duplicated by OCs are not linked to current store blocks and do not leak any access-pattern information.

Data structures. In CAOS each store block contains the following: a block identifier block.bid, a block.data to be stored, a block.cns that indicates the number of clients that know that a block is stored at a position, and a timestamp block.ts of when the data was last changed (cf. Fig 1a).

Client local maps are indexed by the block identifier bid, and contain the following: bid.psns enumerates the positions in the store from which the block bid is available, bid.ts stores most up-to-date timestamp observed, and bid.of stores positions p observed by the map holder (i.e. client) to have block.cns=|Clients|, where Clients is the set of all clients engaged in our protocol (cf. Fig 1b).

Concurrency. In CAOS access-pattern obfuscation is achieved through shuffling, thus achieving efficient concurrency with direct access for all clients represents a significant challenge. This is especially difficult because in CAOS each client maintains its own map and syncs it with the store independently from other clients during ACCESSRW or ACCESSOC operations. In order to prevent data loss, i.e. that a client looses track of the current data in the store, we ensure that “for each data block, there exists a valid position that is known to all clients”. Maintaining this invariant has lead to two design constraints: (1) we require that for each single block accessed two positions are read and two positions are written on the server store, and (2) CAOS can only handle a single read-only write client that works concurrently with other read-only and/or obfuscation clients. These restrictions are further discussed in Section 5.2.

Shared knowledge between clients is tracked using block.cns and bid.of. All clients start from the same version of the map, which is afterwards maintained independently by each one. The protocol requires clients to signal each other when they perform changes to their local maps (i.e. when reassigning a position or when changing the data in a block). Because the client only has access to one position per block during an access operation, the change produced by the client will be localised to that particular position in the store. The problem is that without any additional signalling other clients...
who are not aware of the change have no way of assessing whether the block stored at a specific position is the correct one (as indicated by their map).

We indicate shared knowledge about a position as follows. Whenever a client makes a change to a block, the value block.cns is set to 1, meaning that only one client, the one that made the change is currently aware of the change. When other clients access this block they can become aware that a reassignment has taken place by comparing the block.bid value stored in the block with the value they were expecting according to their local map. If the values do not match the client will infer that the position used to retrieve the block has been reassigned, and will update their local map accordingly. Similarly, by comparing timestamp data from the local map map[bid].ts and from the retrieved block block.ts clients can determine if the block’s data was updated.

Once a client becomes aware that a block has been reassigned to a new position p (and has performed changes in its local map) it increments block.cns by 1 to signal clients that it is aware of the change. When the block.cns value is equal to the number of clients then all the clients can safely assume they have the same view about what block is stored at position p.

Next we continue by specifying CAOS algorithms.

3.2 Read-write (and read-only) client access

Read-write (RW) clients, such as email SMTP servers, and read-only (RO) clients, such as email readers, perform reading and writing through the function ACCESSRW (cf. Fig 2). We introduce the main function first with calls to several sub-functions that implement required functionality. Each sub-function is subsequently described.

The main ACCESSRW function detailed in Algorithm 1 involves the following 8 main steps:

1. Select positions (line 2,3). First, select a position (line 2) to read/write a block as indicated by the input value bid. Then select a random position to sync to the local map (line 3). The block requested via bid will also be copied to the random position if necessary conditions are met (see Algorithm 5). The SelectPosition() function interacts with the locally stored map data structure and selects a random position for a given block id bid. If no bid is supplied a completely random position is chosen from the set of known store positions.

2. Read positions from store (line 4). Retrieve the block indicated by bid and the random block using previously selected positions and decrypt them.

3. Sync (lines 5,6). Synchronize the metadata from the blocks retrieved with the local client map.

4. Return read data (lines 7-9). Prepare to return data if the operation is READ and the block retrieved is correct. If the block retrieved has a different bid than the one requested the client has to re-run ACCESSRW. The protocol guarantees that every client has a valid position for every block.

5. Replace block data (lines 10,11). If the operation is WRITE replace the current data in req.blk with the input data data.

6. Duplicate block (line 12). Attempt to shuffle store data by coping the req.blk to position cpuy.data, thus increasing the number of positions for req.blk and reducing the available positions for block cpuyblk (see Algorithm 5).

7. Write blocks to store (line 13). Encrypt req.blk and cpuyblk and write them at positions req.p and cpuy.p.

8. Return (line 14). Return result as requested data if op = READ and operation was successful; return null otherwise. Return input data as out if op = WRITE and operation was successful (null otherwise).

3.2.1 Sync function. This function (see Algorithm 2) enables CAOS clients to work concurrently, without having to synchronize their maps to access the store. We do require that once, during the setup phase, clients share the store key and a map from one of the other participating clients. Once a copy of the map has been obtained each client can maintain its own version of the map i.e. mapc.

Intuitively this works as follows: after a block has been retrieved from the store, the client needs to establish if local knowledge about the block is correct, i.e. bid of the retrieved block and the position used to retrieve it are correctly linked, and the time-stamp of the block is not older than the time-stamp stored locally. As such, the
Algorithm 2: Sync metadata between a store block and the local map.

**Input:** block, position, client map

**Output:** block, client map

1. function Sync (block, p, map_p)

   2. if (block.ts < map_p[block.bid].ts) then

      3. remove p from map_p[block.bid].psns and map_p[block.bid].vf;

      4. block.bid ← free;

      5. block.ts ← current.time;

      6. block.cns ← 1;

   7. else

      8. if (block.cns < |clients|) then

         9. if (block.ts > map_p[block.bid].ts) then

            10. clear map_p[block.bid].psns and map_p[block.bid].vf;

            11. set map_p[block.bid].ts to current.time;

       12. if (p ∉ map_p[block.bid].psns) then

          13. move p to map_p[block.bid].psns;

          14. block.cns ← block.cns + 1;

     15. if (block.cns = |clients|) then

        16. add p to map_p[block.bid].vf;

    17. return (block, map_p);

Figure 3: ACCESSOC performs three actions: (1) selects and retrieves two blocks from the store, (2) synchronizes local map with metadata from retrieved blocks, and (3) attempts to replace retrieved blocks with buffered stored blocks.

3.3 Obfuscation client access

In CAOS data shuffling is performed on a single position at a time. This process leaks a lot of information to the store server because every run of the ACCESSRW function links two positions together with high probability (i.e. ideally, we require that the DuplicateBlock function is successful every time).

To mitigate this we use a separate obfuscation client function ACCESSOC as presented in Algorithm 3. This function is identical to the ACCESSRW function as far as the interaction with the store is concerned: two blocks are read from two server positions and two blocks are written to the same positions.

The purpose of the OC is to prevent the store from linking the positions that are duplicated thorough the regular ACCESSRW function. This is done through the use of an OC locally stored buffer. ACCESSOC places the blocks read from the store into its buffer, while blocks chosen at random from those currently stored in the buffer are written back to store. The replacement procedure is bound to the same constraints as when blocks are duplicated by regular clients, so we use the same DuplicateBlock functionality to ensure these are enforced. A detailed version of our method is presented in Algorithm 3.
4 CONCURRENCY AND PARALLEL ACCESS IN CAOS

In CAOS concurrency is supported by design. Regular clients communicate with the store using two messages that are abstracted here as follows: \texttt{READ}(p_1, p_2) and \texttt{WRITE}(p_1, p_2). The message \texttt{READ}(p_1, p_2) is used to request the two blocks located at positions \( p_1 \) and \( p_2 \) in the store. Upon receiving this message the server will lock \( p_1 \) and \( p_2 \) and will return the corresponding blocks to the client. The client will process the data, and will use the blocks metadata to update its local map (cf. Section 3). While the client processes the contents of the blocks the server will keep \( p_1 \) and \( p_2 \) locked. The positions \( p_1 \) and \( p_2 \) are unlocked when the server processes a \texttt{WRITE}(p_1, p_2) message from the client that locked the positions. In the event the client is unable to send a \texttt{WRITE}(p_1, p_2) message a timeout period is used to unlock them.

Recall that the client is interested in retrieving the content of only one of the positions, say \( p_1 \), where \( p_1 \) is chosen randomly from the set of positions associated to a given block id in the client’s local map. The other position \( p_2 \) is chosen from the store at random and is used to duplicate the data from \( p_1 \). As such, a second client can request the same block using different positions. In the event that a second client requests the same positions \( p_1 \) and/or \( p_2 \) while they are locked, the server will inform the client of the lockout through an error message. By running ACCESSRWW again, the second client can select new positions \( p_1' \) and \( p_2' \) to retrieve the requested block and a duplicate-destination block. A detailed instantiation of this procedure is presented in Fig 4.

A secondary benefit from supporting concurrency by design is that it allows parallel access to the store. Because each store access by CAOS functions only affects two positions at a time, regular clients (and OCs) can instantiate multiple ACCESSRWW (or ACCESSOC) operations simultaneously for different blocks. This increases access speeds when the data required is stored in multiple blocks. It also affects the speed of the obfuscation process which can be increased or decreased by adjusting the bandwidth available.

\begin{algorithm}
\textbf{Algorithm 3:} Obfuscation client main access function.
\begin{algorithmic}[1]
\Function{ACCESSOC}{buf, S, map_{oc}, k}
\State \( p_1 \leftarrow \text{SelectPosition}(\text{null}, \text{map}_{oc}) \);
\State \( p_2 \leftarrow \text{SelectPosition}(\text{null}, \text{map}_{oc}) \);
\State \( \text{(bk}_1, \text{bk}_2) \leftarrow \text{READ}(p_1, p_2, S, k) \);
\State \( \text{(bk}_1, \text{map}_{oc}) \leftarrow \text{Sync(bk}_1, p_1, \text{map}_{oc}) \);
\State \( \text{(bk}_2, \text{map}_{oc}) \leftarrow \text{Sync(bk}_2, p_2, \text{map}_{oc}) \);
\State \( \text{(bk}_1, \text{buf}) \leftarrow \text{UpdateBuffer(bk}_1, p_1, \text{buf}) \);
\State \( \text{(bk}_2, \text{buf}) \leftarrow \text{UpdateBuffer(bk}_2, p_2, \text{buf}) \);
\State \( S \leftarrow \text{WRITE}(S, k, \text{bk}_1, \text{bk}_2, p_1, p_2) \);
\State \Return{(S, \text{map}_{oc})} \EndFunction
\end{algorithmic}
\end{algorithm}

Figure 4: Concurrent access in CAOS. Upon receiving a \texttt{READ}(p_1, p_2) message the server locks requested positions \( p_1 \) and \( p_2 \). If receiving a second request for \( p_1 \) and/or \( p_2 \), from a different client (e.g. the OC), the server will reply with an error. The second client can restart the protocol and request a new pair (e.g. \( p_1' \) and \( p_2' \)). Positions are unlocked after the server processes the \texttt{WRITE} position message (e.g. \texttt{WRITE}(p_1, p_2)) or \texttt{WRITE}(p_1', p_2').

5 CONTENT AND ACCESS-PATTERN PRIVACY FOR CAOS AND PROTOCOL CORRECTNESS

In this section we give a formal definition of content privacy and pattern access privacy for CAOS-like protocols. Next we analyse the privacy offered by our proposal CAOS. Finally, we present our invariants which ensure that our asynchronous concurrency protocol does not result in unintentional data loss.

5.1 Game-based privacy for CAOS

We start with the following definition.

\textbf{Definition 5.1.} The access-pattern induced by the \( i \)-th run of the ACCESSRWW or ACCESSOC algorithms of a CAOS-like protocol \( O \) is the tuple \( A^i = (p_1, \ldots, p_m, p_{m+1}, \ldots, p_{m+i}) \), consisting of the \( i \) positions read by the server and the \( m \) positions written by the server. The access-pattern induced by a sequence of queries is the combination of the patterns induced by the individual queries.

\textbf{Attacker Model.} When the algorithms ACCESSRWW and ACCESSOC are run, the adversary learns the access-pattern induced by those queries. The attacker is given access to the setup algorithms \texttt{INIT,STORE} and \texttt{INIT,OC}, and thus knows the initial layout of the store and OC buffer.

Using the access-pattern definition above we define the security of a generic CAOS-like construction \( O \) against a multiple query attacker in the following.

\textbf{Definition 5.2 (data and access-pattern privacy).} CAOS data and access-pattern privacy is defined through a multiple query security experiment as follows (see also Fig 5). Let \( O = (\text{KGen, INIT,STORE, INIT,OC, ACCESSRWW, ACCESSOC}) \) be a CAOS-like protocol over
an \((n, N)\) store \(S\), \(\lambda\) a security parameter, \(r\) be number of rounds the OC is run, and \(b \in \{0, 1\}\). Let \(\mathcal{A} = (\mathcal{A}_{1,1}, \ldots, \mathcal{A}_{1,q}, \mathcal{A}_2)\) be a \(q\)-query adversary. Let \(DB\) be a database. We consider \(\text{Exp}_m^b(\mathcal{O})\), a probabilistic experiment defined in terms of a game played between an adversary \(\mathcal{A}\) and a challenger \(C\), consisting of:

1. **Setup.** \(C\) runs \(\text{KGen}(1^\lambda)\) to create a symmetric key \(k\), and runs \((\text{INIT.STORE}, \text{INIT.OC})\) to initialize the store and the OC’s internal buffer.

2. **Query.** During each query \(j\):
   - **Obfuscation.** \(C\) runs the obfuscation algorithm \(\text{ACCESSOC}(S, k)\), \(r\) times.
   - **Challenge.** \(\mathcal{A}_1\) chooses two block id’s, \(B_0\) and \(B_1\), two operations \(o_{p_0}\) and \(o_{p_1}\), and two data contents \(d_0, d_1\) to be written if any of \(o_{p_0}\) or \(o_{p_1}\) is a write operation. \(C\) runs \(\text{ACCESSRW}(B_0, o_{p_0}, d_0, B_1, o_{p_1}, d_1, S, k)\).

3. **Guess.** \(\mathcal{A}_2\) computes a guess \(b' \in \{0, 1\}\), winning the game if \(b' = b\). The output of the experiment is \(b'\).

The **advantage of a multiple query adversary** \(\mathcal{A} = (\mathcal{A}_{1,1}, \ldots, \mathcal{A}_{1,q}, \mathcal{A}_2)\) against the data and access-pattern privacy of a CAOS-like protocol \(\mathcal{O}\) is defined as:

\[
\text{Adv}_{\mathcal{A}}(\mathcal{O}) = \Pr[\text{Exp}_{m,\mathcal{A}}^0(\mathcal{O}) = 1] - \Pr[\text{Exp}_{m,\mathcal{A}}^1(\mathcal{O}) = 1].
\]

Let us argue that the security experiment above captures both content and access-pattern privacy for CAOS-like protocols. Data privacy against the server is captured by letting the adversary choose two equal-sized data blocks \(B_0\) and \(B_1\) (indexed by their block id’s) before every \(\text{ACCESSRW}\) query. The read-write (read-only) client will call \(\text{ACCESSRW}\) on data block \(B_0\), where \(b \in \{0, 1\}\) is unknown to the adversary. On the other hand, access-pattern privacy against the server is captured by an adversarial choosing of the operation to be performed, i.e. either \(o_{p_0}\) or \(o_{p_1}\), depending on the value of \(b\) that is unknown to the adversary. During the experiment, the adversary \(\mathcal{A}\) has full knowledge of the instructions run and the changes occurred in the store when the read-only (read-write) and obfuscation clients will be calling the algorithms \(\text{ACCESSRW}, \text{ACCESSOC}\) as defined by the corresponding protocol \(\mathcal{O}\). The attacker’s advantage as defined above measures how well the adversary does in gaining knowledge on \(b\) by querying \(\text{ACCESSRW}, \text{ACCESSOC}\) a number \(j\) of times. We obtain the following result:

**Theorem 5.3.** CAOS has content and access-pattern privacy, i.e. the advantage of any multiple query adversary against the privacy of \(\mathcal{O}\) is negligible in the security parameter \(\lambda\) and the number of OC rounds \(r\).

See Appendix C for a proof.

### 5.2 Invariants in CAOS

Different clients hold different position maps, and therefore it is possible that a client’s position map will be out of date. Being a little bit out of date is not a problem: if a client seeks a block at a position and finds a different block there, the client can detect that, and seek the block at another position. However, we need to ensure that a client will always eventually find the block. We therefore prove the following invariant: **for every client and every block, the client has a valid position for the block in its map.** See Appendix D for a proof.

## 6 PERFORMANCE AND IMPLEMENTATION

The security of CAOS derives from the fact that the obfuscation client (OC) runs in between the accesses made by the regular clients. Intuitively, the more runs of OC, the more secure the system. In this section, we derive the expected number of rounds of OC needed to get perfect security (i.e. a situation in which the adversary has no knowledge of what block is in what position). In our algorithm, OC processes two positions per round. For simplicity, in this section, we consider an OC that processes a single position per round. Intuitively, the performance of the two-round OC is no worse than a one-round OC.

**Theorem 6.1.** The expected number of rounds of OC needed to obtain perfect privacy for a \((n, N)\) store is at most \(2s + (n - s)\log(n - s) + N\log N\), where \(s\) is the OC’s buffer size.

Since \(N\) is much greater than \(n\) and \(s\), this is dominated by \(N\log N\). Intuitively, perfect privacy cannot be achieved with less than \(N\) rounds, since every store position needs to be updated. See Appendix B for a proof.

### 6.1 Performance

We next report on the performance of our instantiation of CAOS in terms of storage and bandwidth, and present measured data from a non-optimized implementation of our protocol [1] for a 64GB store size.

**Read-write client.** Client storage in CAOS is limited to the client map and the two blocks from the store retrieved by the \(\text{ACCESSRW}\). These, however, are only stored only for the duration of the method run.

Our bandwidth requirements are constant: two blocks are accessed for each requested data block from the store. Because the storage server only locks the positions requested for the duration of a client access, multiple blocks can be requested simultaneously in a parallel manner.
Obfuscation client. The OC accesses the store the same way the RW client does, hence the bandwidth requirements per block are the same. The OC requires additional storage than the read-write client in the form of a local buffer which is needed for the obfuscation process. In Appendix B we show how to compute \( r_1 \) the number of rounds required to obtain secure output from the OC for any given buffer size \( s \). We note that the rate given by Eq. 1, Appendix B is valid for a single positions processed per round. Given that the OC behaves identical to the read-write client implies that the rate is in fact doubled.

Similarly, one can also compute an upper bound on the number of rounds needed to bring the store from a completely insecure state (i.e. adversary knows the contents of each position) to a secure state using Eq. 2, Appendix B.

Storage server. In order for our CAOS protocol to guarantee that blocks can be shuffled between positions it is required that each block is stored redundantly on a number of positions equal to the number of clients using CAOS. However, if the additional space is not available when the store is initialised, our protocol will automatically adjust itself allowing the size of the store to be increased gradually.

Implementation. We have implemented CAOS in C++ using the OpenSSL-1.0.2k for the encryption operations (concretely we use AES-128 in CBC mode) and Protocol Buffers\(^2\) for network message serialisation. Our setup consists of a server which exposes a block-store API with direct access to disk. The server’s API is addressable through positions. In addition to the server we implemented a RW client and an OC client which are able to run ACCESSRW and ACCESSOC respectively.

On an Intel i5-3570 CPU at 3.40GHz running ArchLinux we have instantiated a secure store of 64GB with a redundancy factor \( C = 2 \) (i.e. every block is stored on two positions resulting in \( N = 2n \)). We measured the read/write speed to the store, client storage and server storage. Our results are presented in Table 1.

### 7 CONCLUSION

In this paper we have proposed Concurrent-Access Obfuscated Store (CAOS), a cloud storage solution that is able to provide access-pattern obfuscation. We have presented our concurrent access protocol that allows multiple read-only clients to simultaneously access a CAOS store. We have proved that the concurrent access does not result in data loss. We have also proven the security of our protocol for any buffer size \( s \) used by the obfuscation client given a sufficient numbers of rounds \( r \). Finally, we have shown that security provided by the CAOS protocol is proportional to the resources provisioned for access-pattern obfuscation, namely the buffer size \( s \) and the number of rounds \( r \). To our knowledge, there is no existing work that uses an obfuscation client to hide access patterns. However several works have been influential in the development of CAOS, and we list them in Appendix ??.

### REFERENCES


\(^2\)https://developers.google.com/protocol-buffers

<table>
<thead>
<tr>
<th>Store capacity</th>
<th>Protocol ( \mathcal{O} ) Sc. 3</th>
<th>Instantiation with ( n = 10^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server storage requirements</td>
<td>( C \cdot n \cdot</td>
<td>\text{block}</td>
</tr>
<tr>
<td>RW/RO client storage requirements</td>
<td>( c \cdot n (c \ll 1) )</td>
<td>55 MB</td>
</tr>
<tr>
<td>RW/RO client bandwidth</td>
<td>( p_{s_1} \cdot 2 \cdot</td>
<td>\text{block}</td>
</tr>
<tr>
<td>OC buffer size</td>
<td>( z \cdot</td>
<td>\text{block}</td>
</tr>
<tr>
<td>OC bandwidth</td>
<td>( p_{s_2} \cdot 2 \cdot</td>
<td>\text{block}</td>
</tr>
</tbody>
</table>

Table 1: Storage and bandwidth requirements to store of \( n \) data blocks of size \( |\text{block}| \) bytes in our CAOS instantiation. \( c, C \) are constants that are implementation-dependent and \( p_{s_1} \) and \( p_{s_2} \) are the number of parallel sessions run by the client and by the OC respectively. Figures are given in a generic notation (middle column), and as obtained from our own non-optimized implementation of the protocol (right column).

A CAOS USE-CASE EXAMPLE

Alice wishes to move her 1TB encrypted email store to the cloud, for easy access from her three devices: a work computer, a laptop, and a mobile device. She also requires that her devices have simultaneously access and access-pattern protection.

One option for Alice is to use an ORAM scheme \([10, 16, 22]\) as they provide both data encryption and access-pattern security with \(O(\log N)\) efficiency. With ORAM, Alice can expect to download and upload an average of about 468KB of data\(^3\) for each 30KB email message she wants to access.

To enable simultaneous access for her devices she can use a proxy-based ORAM scheme \([17, 20]\). This would allow Alice’s devices to use less bandwidth, because they would interact with the proxy, however, the bandwidth between the proxy and the store will remain similar (i.e. \([20]\) requires 30MB/s to provide 1MB/s access to the store, \([17]\) requires a transfer of 256KB to access a 4KB store block). Unfortunately, the high bandwidth and computational requirements might force Alice to place the proxy in the cloud, an option she does not like because then access patterns to the proxy would leak information.

An alternative option for Alice would be to use CAOS. In CAOS her devices would have simultaneous and direct access to the store. Access-pattern obfuscation would be done by OCs which can be placed either in the cloud or on the premises because they access the store independently from her devices. However, access operations in CAOS randomize the store, and Alice’s devices and OCs would require some form of synchronisation between them to be able to access it.

One naïve CAOS implementation which solves the synchronisation problem is to separate a part of the store, share it between devices and OCs, and use it to log the changes. During each access, clients would be able to process the log and update their access information (i.e. maps). However, if Alice were to stop using any one of her 3 device for just a month, assuming use, that device will have to process around 46MB worth of log entries\(^4\) only to access a 30KB index, as the log grows linearly with the number of

\[^3\text{For a 1TB ORAM store which uses 4KB blocks and 4 blocks per bucket, the size of transferred data is between 104KB and 832KB, depending on how the data is laid out in the server’s memory and the ORAM scheme used.}\]

\[^4\text{This number assumes that a log entry is 1KB, and that the remaining 2 devices will only access a 30KB email index that uses 8 blocks, 6 times per hour, 16 hours per day for 30 days. The number does not account for any OCs doing access-pattern obfuscation, in which case the number would be much higher.}\]
below it. Then one has to wait \((n - s)/2\) more rounds before a card is again inserted below the original bottom card. Continuing in this way, the number of rounds needed for the original bottom to get to the U/V threshold is

\[
(n - s) + \frac{n - s}{2} + \frac{n - s}{3} + \cdots + \frac{n - s}{n - s} \leq 1 + (n - s) \log(n - s).
\]

A further \(s\) rounds are needed for the original bottom to progress from the U/V threshold to the top of the deck. Thus, the total number of rounds is \((n - s) \log(n - s) + s\). Since OBS is no worse than OBS\(^\prime\), we have

\[
r_1 \leq 1 + (n - s) \log(n - s) + s.
\]

Calculation of \(r_2\) is similar. The first of the \(N\) positions is overwritten in one round. For the second position to be overwritten, we have to wait \(N/(N - 1)\) rounds; this is a bit longer, because we may accidentally overwrite the first one again. The \(i\)th position requires us to wait \(N/(N - i)\) rounds. Thus, all the positions are overwritten after an expected

\[
r_2 = 1 + \frac{N}{N - 1} + \cdots + N \leq 1 + N \log N
\]

(2) rounds. Therefore, \(r_1 + r_2 \leq 2 + (n - s) \log(n - s) + s + N \log N\). \(\square\)

**C ANALYSIS OF CAOS CONTENT AND ACCESS-PATTERN PRIVACY**

Our aim now is to analyze privacy offered by CAOS against a multiple query adversary. To this end, we need to make use of two lemmas, starting with the following lemma.

**Lemma 1.** Let \(S\) be the \((n, N)\) CAOS-like store with \(N = \{p_0, \ldots, p_{N - 1}\}\) positions. Suppose that our ACCESSSOC is run \(r\) times. Let \(\text{no}(p_i)\) be the event that the position \(p_i\) was not overwritten during the \(r\) rounds. The probability that, after \(r\) runs of the ACCESSSOC method, at least one of the \(N\) positions has not been overwritten (i.e., at least one position survived being overwritten) is:

\[
p_{N, r} = \Pr\left[\text{no}(p_0) \lor \cdots \lor \text{no}(p_{N - 1})\right] = 1 - N(\frac{1}{N} \cdot \frac{N - 1}{N} \cdot \cdots \cdot \frac{N - r + 1}{N})^r
\]

(3)

In order to increase its advantage in the privacy game, the adversary uses as leverage its knowledge of which blocks are in which positions in the store, and what blocks are in the OC buffer. As OC runs, the adversary might try to track the movement of blocks. We can model the adversary’s knowledge of what is inside the OC buffer as a probability distribution.

Suppose the buffer size is \(s\). The OC buffer contains at most one occurrence of a given block id. Our goal in following is to describe the evolution of the adversary’s knowledge as a probability distribution. We start by recalling that, at each step, OC selects a block to be added to the buffer. If the selected block id is already in the buffer, then the set of block ids in the buffer is not changed. But if the selected block is not currently in the buffer, then one of the buffer’s slots is chosen (with uniform probability) and the block id in that slot is evicted, in order to add the selected one.

Therefore, the buffer contents will be \(X\) after such a step if:

1. The buffer contents were already \(X\), and an element in \(X\) was selected; or
2. For some \(x \in X\) and \(e \not\in X\), the buffer contents was \((X - \{x\}) \cup \{e\}\), and \(x\) got selected for adding to the buffer, and \(e\) was chosen for eviction from the buffer and gets put back in the store where \(x\) had been.

We view this as a system of states and transitions. A state is the pair \((X,\text{sel})\), where \(X\) is a set of block ids, and \(\text{sel}\) is a function from block ids to reals that abstracts the store. The value \(\text{sel}(x)\) is the probability that a position in the store chosen uniformly at random contains block id \(x\). Since \(x\) must occur at least once in the store, and since every other block must also occur at least once, \(x\) appears at least once and at most \(N - n + 1\) times. Therefore, for any \(x\), the value \(\text{sel}(x)\) is in the set \(\{\frac{1}{N}, \frac{2}{N}, \ldots, \frac{N-n+1}{N}\}\).

There are two kinds of transition, corresponding to the two points above:

1. For each \(x \in X\): \((X, \text{sel})\) can transition to \((X, \text{sel})\), with probability \(\text{sel}(x)\).
2. For each \(x \in X\) and \(e \not\in X\): \((\{x\} \cup \{e\}, \text{sel})\) can transition to \((X, \text{sel})\), with probability \(\frac{\text{sel}(x)}{s}\) (Here, the notation \(\text{sel}[x] \mapsto \text{expr}\) means the function \(\text{sel}\) but with \(x\) mapping to \(\text{expr}\). The factor \(\frac{1}{s}\) in the transition probability is the probability that \(e\) is evicted.)

This system is easily seen to be a Markov chain with eigenvalues \(1 = |\lambda_1| > |\lambda_2| \geq \cdots \geq |\lambda_n|\). Moreover, this Markov chain describes a random walk in a strongly connected Eulerian digraph in which nodes represent the possible states \((X, \text{sel})\) and the edges represent the transitions between them.

Let us write \(\text{inb}_j(X)\) for the probability that, after the \(j\)th run, the set of block ids present in the buffer is \(X\). We can state the following lemma.

**Lemma 2.** Let \(\text{out}_j(B)\) be the probability that the block coming out of an OC with buffer sizes \(s\) at the \(j\)-th step is the block \(B\). For all \(j, j' > r\) and initial distributions \(\text{inb}_0\), the probability \(\text{out}_j(B) - \text{out}_{j'}(B)\) is at most

\[
\left(\frac{n - 1}{s - 1}\right) \cdot C \cdot |\lambda_2| ^ r
\]

for some constant \(C\) and \(\lambda_2 < 1\), and is therefore negligible in \(r\).

**Proof.** Let \(P\) be the transition matrix for this Markov chain. Then \(P\) is stochastic, irreducible and aperiodic. Let \(\pi\) be the probability distribution after \(j\) steps. Then \(\pi_j = \pi_0 \cdot P^j\). Let \(\lambda_1\) and \(\lambda_2\) be the largest and second-largest eigenvalues of \(P\). Overwhelmingly likely, the eigenvalues are all distinct. Since \(P\) is stochastic, \(\lambda_1 = 1\) and \(\lambda_2 < 1\). Applying the Perron-Frobenius Theorem similarly to Backaker [4, Theorem 3 and Example 1], we have \(P^j = P^\infty + O(|\lambda_2|^j)\), and therefore \(\pi_j - \pi_j' = \pi_0 \cdot C' |\lambda_2| ^ r\) for \(j, j' > r\) for some constant \(C'\).

Let \(\pi(X, \text{sel})\) be the probability that the state is \((X, \text{sel})\) in the probability distribution \(\pi\). Then \(\text{inb}_j(X) = \sum_{\text{sel}} \pi_j(X, \text{sel})\). Let \(m_{j, j'} = \max_X (|\text{inb}_j(X) - \text{inb}_{j'}(X)|)\), where \(X\) ranges over sets of block ids of size \(s\). Then, for \(j, j' > r\),

\[
m_{j, j'} = \max_X (|\sum_{\text{sel}} |\pi_j(X, \text{sel}) - \pi_{j'}(X, \text{sel})|) = \max_X (|\sum_{\text{sel}} |\pi_0(X, \text{sel}) - C' |\lambda_2| ^ r|) = C' |\lambda_2| ^ r \cdot \max_X (|\sum_{\text{sel}} \pi_0(X, \text{sel})|).
\]
Notice that \( \text{out}_j(B) = \sum_{X | B \in X} \text{inb}_j(X) \). Therefore,
\[
|\text{out}_j(B) - \text{out}_j(B)| = \sum_{X | B \in X} |\text{inb}_j(X) - \text{inb}_j(X)| \\
\leq \left( \frac{n-1}{s-1} \right) \cdot m_{ij,j'} \\
\leq \left( \frac{n-1}{s-1} \right) \cdot C \cdot |\lambda_2|^r
\]
where \( C = C' \cdot \max \{ \sum_{\text{sel}} \pi_0(X, \text{sel}) \} \).

\( \Box \)

**Theorem C.1.** CAOS has content and access-pattern privacy, i.e. the advantage of any multiple query adversary against the privacy of CAOS is negligible in the security parameter \( \lambda \) and the number of OC rounds \( r \).

**Proof.** We bound the distinguishing advantage of any CAOS adversary through the following sequence of "game hops".

**Game 1.** This is the legitimate \( \text{Exp}^0_{m,A}(O) \) experiment. In particular, in the \( j \)-th challenge query \( C \) returns ACCESSRW \( (B_0, i, \sigma_0, j, \sigma_0, j, 0, j, S, k) \), for \( j = 1, \ldots, q \).

We define the following sequence of experiments for \( j = 1, \ldots, q \).

**Game 2, j.** Let \( j \in \{ 1, \ldots, q \} \) is fixed. In this experiment, the queries \( i = 1, \ldots, j \) are answered with ACCESSRW \( (B_0, i, \sigma_0, j, d_i, S, k) \), namely by performing operation \( \sigma_0 \) on block \( B_0 \) with data \( d_i \) (instead of data \( \sigma_0 \)). The remaining queries until the \( q \)-th query are responded normally, i.e. with \( \text{ACCESSRW}(B_0, i, \sigma_0, d_0, d_0, S, k) \) for \( i = j + 1, \ldots, q \).

Let us call this modified experiment \( \text{Exp}^{2,j}_{m,A}(O) \). One can easily see that
\[
\mathbb{P} \left[ \text{Exp}^{2,j}_{m,A}(O) = 1 \right] = \mathbb{P} \left[ \text{Exp}^{2,j}_{m,A}(O) = 1 \right]
\]
for \( j = 1, \ldots, q \) is upper-bounded by the distinguishing advantage against the semantic security of the encryption scheme, which is negligible [5]. Trivially \( \text{Exp}^{2,0}_{m,A}(O) = \text{Exp}^{0}_{m,A}(O) \).

Next, for \( j = 1, \ldots, q \) we define a new sequence of experiments.

**Game 3, j.** Fix \( j \). In this experiment, the queries \( i = 1, \ldots, j \) are answered with ACCESSRW \( (B_1, i, \sigma_0, d_1, S, k) \), i.e. by running operation \( \sigma_0 \) on block \( B_1 \) with data \( d_1 \) (instead of running it on block \( B_0 \)). The remaining queries until the \( q \)-th query remain unchanged, i.e. they return ACCESSRW \( (B_0, i, \sigma_0, d_1, S, k) \) for \( i = j + 1, \ldots, q \). Let us call resulting experiment \( \text{Exp}^{3,j}_{m,A}(O) \).

We proceed to upper bound the probability that an adversary has in distinguishing access to two different blocks \( B_{i,j} \) and \( B_{i,j} \) in experiment \( \text{Exp}^{3,j}_{m,A}(O) \).

Consider the \( r \) runs of OC. Let \( r_1 = r \); we will distinguish between the first set of \( r_1 \) runs, and the remaining \( r - r_1 \) runs. Now we distinguish between two situations that arise after the runs:

**State A** The adversary has observed that all the positions in the store got overwritten by a block id coming out of OC during the second set of \( r - r_1 \) runs.

**State B** The adversary has observed that not all the positions got overwritten; that is, at least one position survived being overwritten during the second set of \( r - r_1 \) runs.

When a store position is overwritten at step \( j \) by a block coming from OC, the adversary’s probability distribution of what block is in that store position is \( \text{out}_j(B) \). If State A is observed, then the adversary’s probability of distinguishing the block read in ACCESSRW is at most
\[
\max_{B_{i,j}, B_{i,j}} \left[ \mathbb{P} \left[ S_1 \text{ contains } B \right] - \mathbb{P} \left[ S_1 \text{ contains } B \right] \right]
\]
which is at most \( n_i, j, j' \cdot |\text{out}_j(B) - \text{out}_j(B)| \). By Lemma 2, this value is at most \( \left( \frac{n-1}{r} \right) \cdot S_r \).

The probability that state \( B \) is observed is \( p_{N,r} \) (this notation is defined in Lemma 1).

The probability of distinguishing is the probability of arriving in state A times the probability of distinguishing in state A, plus the probability of arriving in state B times the probability of distinguishing in state B. This is at most:
\[
(1 - p_{N,r}) \cdot \left( n_i, j, j' \right) \cdot S_r + p_{N,r} \times 1
\]

Since both \( S_r \) and \( p_{N,r} \) are negligible in \( r \), the probability and therefore the advantage of the adversary is negligible in \( r \).

Let us define the last series of game hops, again for \( j = 1, \ldots, q \).

**Game 4, j.** In this experiment, the queries \( i = 1, \ldots, j \) are answered with ACCESSRW \( (B_{i,j}, \sigma_0, d_1, S, k) \), i.e. by running operation \( \sigma_0 \) on block \( B_{i,j} \) with data \( d_1 \) (instead of running operation \( \sigma_0 \)). The remaining queries until the \( q \)-th query remain unchanged, i.e. they return ACCESSRW \( (B_{i,j}, \sigma_0, d_1, S, k) \) for \( i = j + 1, \ldots, q \). Let us call resulting experiment \( \text{Exp}^{4,j}_{m,A}(O) \). Actually, it holds that
\[
\mathbb{P} \left[ \text{Exp}^{4,j}_{m,A}(O) = 1 \right] = \mathbb{P} \left[ \text{Exp}^{4,j}_{m,A}(O) = 1 \right]
\]
by construction. This is because ACCESSRW performs the same (read position followed by write position) both for read and write operations. It is easy to see that \( \text{Exp}^{4,j}_{m,A}(O) = \text{Exp}^{1}_{m,A}(O) \).

Finally, by adding the probabilities obtained in each game hop, the statement of the theorem follows.

\( \Box \)

**D INVARIANTS**

We prove the following invariant: for every client and every block, the client has a valid position for the block in its map (INV-2 below). In the following we will use \( \text{block}[p] \) notation to denote the block contained at position \( p \) in the server store, and \( \text{map}_C[B] \) to denote the entry for block id \( B \) in the map of client \( C \).

We start with a simpler invariant, which is a useful lemma.

**INV-1.** The variable \( \text{block}[p].\text{cns} \) on the server is at most equal to the number of clients that know that that block is at position \( p \). More precisely: for all positions \( p \),
\[
\text{block}[p].\text{cns} = \left[ \{ C | \text{Clients} \} \right] \land \text{map}_C[\text{block}[p].\text{bid}].\text{psns} \land \text{map}_C[\text{block}[p].\text{bid}].\text{ts} = \text{block}[p].\text{ts}
\]

The code maintains this invariant by linking any change to the local map with an operation on the \( \text{block}[p].\text{cns} \) value. These changes happen when the contents of the block is updated or deleted (by marking the block as free). The SyncPositions operation (see
Algorithm 2 updates a client’s local map to reflect changes performed by other clients and frees old data. The WriteBlock and DuplicateBlock set the \( \text{block}[p].\text{cns} \) value to 1 in order to trigger map changes in other clients.

As a corollary, we have the following:

\( \text{INV-1} \). When \( \text{block}[p].\text{cns} \) has the maxim value (\(|\text{Clients}|\)), then every client’s local map contains the latest information about position \( p \). More precisely, for each \( p \):

\[
\forall C \in \text{clients}, \ p \in \text{map}_C[\text{block}[p].\text{bid}].\text{psns} \wedge \text{map}_C[\text{block}[p].\text{bid}].\text{ts} = \text{block}[p].\text{ts}  
\]

\( \text{INV-2} \). For each block, a valid position is always known to all CAOS clients. More precisely, for any block id \( B \), there is a position \( p \) such that

\[
\text{block}[p].\text{bid} = B \wedge p \in \bigcup_{C \in \text{clients}} \text{map}_C[B].\text{psns}
\]

Before we prove this invariant, we provide some intuition. To maintain \( \text{INV-2} \), we use the \( \text{map}[B] \) set stored in the client’s map. This set tracks which are the positions \( p \) of a block that a client has observed to have a maximum value for \( \text{block}[p].\text{cns} \). In order to prevent data loss, we require that (1) at any time each client can only reassign a single position, and (2) that at least one position still remains if all the clients decide to reassign one position.

The second part of the requirement (2) is easily achieved by checking that the size of \( \text{map}[B] \). \( \text{vf} \) is bigger than the number of clients. We address the first requirement (1) by requiring each client mark the \( \text{map}[B] \). \( \text{vf} \) set as empty whenever they reassign a position from it. This will prevent the client to reassign any consolidated positions until it re-learns their location.

**Proof.** We prove it for the case that there are two clients, say \( C \) and \( D \); as will be seen, the proof generalises intuitively to more clients. Suppose \( \text{INV-2} \) is not an invariant; then there is a transition from a state \( st_k \) in which \( \text{INV-2} \) holds for a block id \( B \), to a state \( st_4 \) in which it does not hold for \( B \). Suppose client \( C \) reallocates the crucial position \( p \) in \( st_k \) which is lost in \( st_4 \). Since \( st_k \) satisfies \( \text{INV-2} \), in \( st_k \) \( p \in \text{map}_C[B].\text{psns} \) and \( p \in \text{map}_D[B].\text{psns} \), and since \( st_4 \) does not satisfy \( \text{INV-2} \), in \( st_4 \) \( \text{map}_C[B].\text{psns} \cap \text{map}_D[B].\text{psns} = \emptyset \). Using Algorithms 2 and 5, we see that the transition for \( C \) from \( st_k \) to \( st_4 \) required \( |\text{map}_C[B].\text{vf}| > 2 \) in \( st_k \), so suppose that \( \text{map}_C[B].\text{vf} \subseteq \{q, r\} \) in \( st_3 \). Since \( \text{vf} \subseteq \text{psns} \) (Algorithms 2 and 5), we have \( \{p, q, r\} \subseteq \text{map}_C[B].\text{psns} \) in \( st_k \).

Let \( st_k \) be the state immediately after the previous reallocation by \( C \). Then \( \text{map}_C[B].\text{vf} = 0 \) in \( st_k \). Since \( q, r \in \text{map}_C[B] \). \( \text{vf} \) in \( st_k \), there was a state between \( st_0 \) and \( st_3 \) in which \( q.\text{cns} = 2 \), and one in which \( r.\text{cns} = 2 \). Let \( st_l \) be the most recent of those states. Either \( q \) or \( r \) was reallocated between \( st_l \) and \( st_k \), and by definition of \( st_l \), that reallocation was done by \( D \). Consider the most recent reallocation by \( D \) done before \( st_k \), say in a state \( st_2 \). Now we have states \( st_0, st_1, st_2, st_3, st_4 \) in temporal order. Based on Algorithms 2 and 5, \( \text{map}_C[B].\text{vf} > 2 \) in \( st_2 \), so say \( \text{map}_D[B].\text{vf} \supseteq \{t_1, t_2, t_3\} \). Then, in \( st_2 \) we have: \( \text{block}[t_1].\text{cns} = \text{block}[t_2].\text{cns} = \text{block}[t_3].\text{cns} = 2 \), and by \( \text{INV-1} \), \( \{t_1, t_2, t_3\} \subseteq \text{map}_C[B].\text{psns} \cap \text{map}_D[B].\text{psns} \). In \( st_2 \), \( D \)'s transition has removed one element from \( \text{map}_D[B].\text{psns} \), and in

\( st_4 \), \( C \)'s transition has removed one element from \( \text{map}_C[B].\text{psns} \). Therefore, in \( st_4 \), \( \text{map}_C[B].\text{psns} \cap \text{map}_D[B].\text{psns} \) is non-empty, contradicting our hypothesis.

**E ALGORITHMS**

**Algorithm 4:** Write a block to the store.

**Input:** block id, block, data  
**Output:** block, status

```
function PrepareWrite (bid, block, data)  
  if (block.bid = bid or block.bid = free) then  
    block.bid ← bid;  
    block.data ← data;  
    block.\text{cns} ← 1;  
    block.ts ← \text{current.time};  
    status ← block.data;  
  else  
    status ← null;  
  return (block, status);  
```

**Algorithm 5:** Duplicate a store block to a new position.

**Input:** source block, destination block, destination position  
**Output:** destination block, client map

```
function DuplicateBlock (sblock, dblock, p, map_c)  
  if (dblock.\text{cns} = |\text{clients}| and  
      |\text{map}_{d} \text{[dblock.bid].vf}| > |\text{clients}|) or  
      (dblock.\text{cns} = 1 \text{ and } |\text{map}_{d} \text{[dblock.bid].psns}| > 1)) then  
    dblock.bid ← sblock.bid;  
    dblock.data ← sblock.data;  
    dblock.ts ← sblock.ts;  
    dblock.\text{cns} ← 1;  
    clear map_{d} \text{[dblock.bid].vf};  
    move p from map_{d} \text{[dblock.bid].psns} to  
    map_{d} \text{[sblock.bid].psns};  
  return (dblock, map_c);  
```

**Algorithm 6:** Update the local buffer data structure.

**Input:** block, position, buffer, obfuscation client map  
**Output:** block, buffer

```
function UpdateBuffer (blk, p, buffer, map_w)  
  if (buffer not full) then  
    add blk to buffer;  
  if (buffer is full) then  
    remove blk from buffer;  
  return (blk, buffer);  
```