ConcurORAM: Multi-client concurrency for RingORAM

ABSTRACT

Oblivious RAM (ORAM) technology has advanced rapidly in recent years as an increasing amount of data is outsourced to remote storage. Although tree based ORAMs such as PathORAM and RingORAM have achieved nearly-optimal bandwidth blowup for *single client* scenarios, the low overall throughput due to high latency of access makes them prohibitive in multi-client scenarios.

In this paper, we propose ConcurORAM, a multi-client concurrent variant of RingORAM that reduces waiting for concurrent client accesses and increases overall throughput by a factor of the number of clients. Our concurrency mechanism is based on the concurrency mechanism proposed in [21].

We leverage the asynchronous nature of RingORAM queries to support concurrent client accesses up-to an eviction. Further, we use a pyramid ORAM using the PD-ORAM abstraction detailed in [21] for concurrent accesses to the position map.

1. INTRODUCTION

With an increasing amount of confidential data being stored on outsourced storage, the privacy of this data is of critical importance. As demonstrated in previous work [11], simply encrypting the data is not enough. Even on encrypted data, the sequence of locations read and written to the storage can leak information regarding the user's *access pattern* and the data stored.

Oblivious RAM (ORAM) is a cryptographic primitive that allows a client to hide its data access patterns from an untrusted storage hosting the data. Informally, the ORAM adversarial model prevents an adversary from distinguishing between multiple equal length sequence of queries made by the client to the server.

Since the original ORAM construction by Goldreich and Ostroevsky [6], a large volume of previous literature [8, 15, 16, 18, 20, 21] has been dedicated to developing more efficient ORAM constructions. PathORAM [18], based on the original binary tree ORAM construction by Shi *et al.* [16] is widely accepted to be asymptotically the most *bandwidth efficient* ORAM. RingORAM [15] further improves on the practical overhead of PathORAM [18] by optimizing the constants. Even for ORAMs that divide the data into multiple sub-ORAMs such as ObliviStore [17] and CURIOUS [2], [2] shows that PathORAM [18] is the most suitable ORAM for sub-ORAM design in terms of cost and bandwidth.

Although, recent tree based ORAM designs have achieved near-optimal *bandwidth* for single client scenarios, one critical challenge, yet to be addresses, is to make these ORAMs compatible for concurrent non-overlapping access (access for different data items) for multi-client scenarios, while maintaining security gaurantees. As a motivating example, consider an enterprise that offloads confidential data to a remote storage that deploys an ORAM, and provides access to a group of employees (users). These users should be able to perform non-overlapping queries without a significant performance overhead compared to a scenario where there is only one user accessing the ORAM.

Note that it is trivial to deploy a standard tree based ORAM without concurrency to support multiple clients by sharing the key to the ORAM and storing all related datastructures (the stash and the position map) on the storage server to ensure consistency of state. In this case, only *one* client can access the position map, the stash and the tree at one time while the other concurrent clients must wait for this client to finish. This reduces the overall throughput and increases the query response time by a factor of the number of concurrent clients. A client (in the worst case) might need to wait for *all* other clients to finish before retrieving the required data item. Since, ORAMs have high latency of access (due to the retrieval of multiple items for one access), this implies that a client would need to wait a significant amount of time before being able to proceed with the query.

In this paper, we propose ConcurORAM , a mechanism to support multi-client concurrency for tree-based ORAMs without sacrificing security. Our work is based on the concurrency scheme proposed by Williams *et al.* [21]. However, there are significant challenges to directly adapting the techniques proposed in [21] for tree based ORAMs. In the following, we discuss these challenges.

Concurrency for position map. First, tree based ORAMs use a position map to store mappings from the logical IDs of data items to the leaf IDs in the tree they are mapped to. Specifically, a data item mapped to leaf ID l can reside in any of the nodes along the path to leaf l from the root. In a single client scenario, the position map can be stored at the client side. For a multi-client scenario the position map must be stored on the server to ensure consistency among the clients. As introduced in [16], the position map can also be stored at the server (to reduce client side storage) in recursively smaller ORAMs. In this case, the position map is divided into fixed size blocks. Thus, an access in this case, requires reading the position map from the smaller ORAMs to obtain the leaf ID for the required data item and then reading the corresponding path to retrieve the data item. Since, the position map is stored recursively, an ORAM storing the position map also has a position map. To ensure that each successive position map is smaller (to ensure that the recursion terminates with an ORAM that has a a constant size position map), each block in the ORAMs must store multiple position map entries. However, using this in a multi-client scenario allows the server to correlate two client accesses if they access the same position map block. Note that two concurrent clients may access the same position map block even if they are not accessing the same data item.

As one of the main insights, ConcurORAM stores the entries of the position map in a pyramid ORAM ([6, 21]) with multiple levels and uses a hash function to map position map entries to buckets in a level. Note that since the location of an entry is randomized (due to the uniform hash function used), concurrent clients accessing the same bucket, does not leak any correlation between the items queried by the clients. Specifically, ConcurORAM use the concurrent version of PD-ORAM as used in PrivateFS [21] to ensure concurrency for queries.

Decoupling fetching and eviction. Tree based ORAMs divide accesses into two parts – fetching data (reading a root to leaf path) and eviction (writing back the read data to a root to leaf path). To ensure consistency in multi-client scenarios, the fetching and eviction cannot proceed concurrently. Thus, the fetching and eviction must be decoupled. Fortunately, RingORAM [15] provides a mechanism to evict data after a fixed number of fetches. ConcurORAM uses RingORAM and support a fixed number of concurrent queries followed by an eviction by a single client.

ConcurORAM has been implementd and shows an increase in throughput by a factor of **[TODO: Anrin: this number to be filled]** over a standard implementation of RingORAM [15] used non-concurrently for multiple clients.

2. RELATED

ORAMs have been well-researched since the seminal work by Goldreich and Ostroevsky [6]. The construction provided by Goldreich and Ostroevsky requires only logarithmic storage at the client side and has an amortized communication complexity of $O(log^3 N)$. ORAM constructions can be broadly classified into two categories: pyramid based construction and tree based constructions. Below we briefly discuss these constructions.

2.1 Pyramid based ORAM

The first pyramid based construction was provided by Goldreich and Ostroevsky [6]. A pyramid based construction organized the data in $logN$ levels. Level i consists of 4^i data blocks assigned to one of 4^i buckets as determined by a secure hash function. Due to hash collisions, each bucket can contain up to $O(lnN)$ blocks.

Read. To obtain a particular block, a client scans *one* bucket from each level as determined by the hash of the logical block ID of that block. The ORAM maintains two invariants: i) a client access never reveals the level at which a block has been found, ii) a block is accessed from a particular location only once. To ensure (i), after a client has found the required block at a particular level, the client continues scanning a *random* bucket from all the levels below it. Once all the levels have been queried, the client reencrypts the accessed block and places it in the top level. This maintains (ii) since it ensures that a block that has been accessed earlier will be located in the top level for the next query for the same block. The rest of the search pattern will be random.

Write. Writes proceed in exactly the same way as the reads with the exception that the updated value of the accessed block is placed in the top level. The same data access pattern for both reads and writes and semantic encryption ensure that the server cannot learn the purpose (read or write) of an access.

Overflow. The top level overflows after a fixed number of accesses since accessed blocks are always placed there. In this case, the top level is merged with the second level and reshuffled using a new secure hash function. The reshuffling is done obliviously using a sorting network [6, 7, 20]. Each level overflows once after the level above has overflown twice. To ensure invariant (i), all buckets contain the same number of blocks (either real or dummy) after a reshuffle.

The most expensive step of the pyramid ORAM is the reshuffle. Various mechanisms have been proposed to make the reshuffle more efficient. Williams and Sion [1] show how to achieve an amortized construction with $O(log^2 N)$ communication complexity under $O(\sqrt{N})$ client storage using an oblivious merge sort. Williams *et al.* further use this mechanism to build an ORAM with $O(logN)$ access complexity and $O(log^2 N)$ overall communication complexity by storing an encrypted bloom filter on the server and retrieving one block from a level.

Pinkas *et al.* [14] use *cuckoo hashing* and randomized shell sort *randomizedshellsort* over the original Goldreich and Ostroevsky solution [6] and achieve an amortized communication complexity of $O(log^2 N)$ with constant client side storage. However, Goodrich *et al.* [9] highlight a leak in the construction in [14] and provide an alternate construction thats achieves an amortized communication complexity of $O(logN)$ under the assumption of $O(N^{1/r})$ client storage with $r > 1$.

Although, the above mentioned constructions improve upon the original solution in [6], client queries still need to wait for the duration of a reshuffle. De-amortized constructions allow queries and reshuffles to proceed together and thus eliminate clients waiting for reshuffles after a level overflow. Goodrich *et al.* [10] show how to de-amortize the original square root solution and hierarchical solution [6] and achieve a worst-case complexity of $O(logN))$ in the presence of $O(n^r)$ client side storage where $r > 0$. In [12], Kushilevitz *et al.* use cuckoo hashing and rotating buffers to provide a de-amortized construction of the original hierarchical solution [6] which achieves a worst-case communication complexity of $O(log^2N/loglogN)$.

PD-ORAM: Unlike the de-amortization techniques used in [10, 12] where each query performs an additional fixed amount of work for the reshuffle, the PD-ORAM [21] de-amortization abstraction performs a reshuffle in the background while monitoring progress to ensure that a level is ready after a reshuffle as soon as it is required. Further, queries can proceed simultaneously through a read-only variant of the level while the reshuffle takes place and ensures roughly similar query costs.

2.2 Tree-based ORAM

In contrast to de-amortized ORAM constructions, tree-based ORAMs are naturally un-amortized (the worst-case query cost is equal to the average cost). A tree based ORAM organizes the data as a binary (or ternary) tree. Each node of the tree is a bucket which can contain multiple blocks. A block is randomly mapped to a leaf in the tree. The ORAM maintains the following invariant: a block resides in any one of the buckets on the path from the root to the leaf to which the block is mapped. The position map which maps blocks to leaves is either stored on the client ($O(N)$ storage required) or recursively on the server for $O(()1)$ client side storage at the cost of $O(log^2N)$ increase in communication complexity.

To access a particular block, the client downloads all the buckets (or one element from each bucket) along the path from the root to the leaf to which the block is mapped. Once the block has been read, it is remapped to a new leaf and *evicted* back to the tree. Various eviction procedures have been proposed in literature [3, 15, 16, 18, 19]

Binary Tree ORAM: The original tree-based ORAM proposed by Shi *et al.* [16] places the accessed block at the root of the tree and evicts a constant number of blocks from nodes at a particular depth to children nodes. In this case, the buckets need to be at least sized $O(logN)$ and the overall access complexity for the construction is $O(log^3N)$.

PathORAM: In PathORAM [18], eviction takes place by writing back the same path that was read and placing the remapped block along the path at a node that intersects with the path to the new leaf to which the block is remapped. Further, PathORAM [18] uses constant sized blocks in the presence of a logarithmic-sized client side *stash* to handle overflows.

RingORAM: RingORAM decouples fetching a path during an access and eviction, by evicting along a deterministically chosen path after a fixed number of fetches. Similar to [5], the path is chosen in the reverse-lexicographical order for better eviction. Further, RingORAM uses larger buckets but reads only one block per bucket during a query as determined by a per-bucket metadata.

2.3 Recent Developments

Recent work [2] has shown that for practical deployment on clouds, ORAMs such as ObliviStore [17] and CURIOUS [2] that divide the data into constant sized sub-ORAMs perform better than both pyramid ORAMs or tree based ORAMs. CURIOUS uses PathORAM as the primitive for the sub-ORAM construction. Alternative ORAM constructions [4, 13] achieve $O(1)$ communication complexity at the cost of server side computation using homomorphic encryption. However, due to expensive homomorphic computations, these ORAMs are not yet practical for deployment.

3. MODEL

Deployment. ConcurORAM considers a deployment model with two parties: the ORAM clients (with limited local storage) and the ORAM server (a remote storage that hosts the clients' data). The server stores data in terms of fixed sized"blocks". ConcurORAM considers N blocks of outsourced data on the server. Clients also access data in blocks addressed by a logical block ID denoted by *id*. The logical address space for all blocks is shared by the clients. The parties engage in an interactive query-response based protocol established by ConcurORAM . The communication channel between the clients and the server is considered secure using SSL.

Clients. Clients are considered honest in the ConcurORAM model and do not interact with each other. Further, the clients share the key to the ORAMs and the secret hash functions used for PD-ORAM, which are stored encrypted on the server. Clients can engage the server without having any knowledge of other client states. Any locking mechanism (as required by the protocol) is imposed by the server. ConcurORAM does not consider the case of malicious clients.

Server. ConcurORAM considers an untrusted server that is honest but curious and does not deviate from the ConcurORAM protocol. The server can observe all requests and try to correlate them by saving and comparing snapshots (state of the server after each query). It stores the ORAM keys, hash functions and other access counters as required by the ConcurORAM protocol. Further, the server maintains and duly increments the counters. ConcurORAM does not consider a malicious server than can mount replay attacks and "fork" client views.

Security challenge. Any system that supports multi-client concurrent access for ORAMs needs to prevent two possible security leaks -

- Correlation between data items concurrently accessed in a single round.
- Correlation between data items accessed in successive rounds of one or more conccurent accesses.

In the above context, we define multi-client concurrent access security for ORAMs as a security game, where the challenger is a fixed set of clients, $\mathcal{C} = \{c_1, c_2, \dots c_n\}$, the adversary, $\mathcal{A}$ is the remote server that hosts a database uploaded by $\mathcal{C}$. All items in the database are indexed and can be accessed concurrently by the clients.

1. $\mathcal{A}$ and $\mathcal{C}$ engage in polynomial rounds of the following query-response based protocol
   (a) $\mathcal{A}$ selects two sets of item indices $\mathcal{O}_1 = \{x_1, x_2, \ldots, x_n\}$ and $\mathcal{O}_2 = \{y_1, y_2, \ldots, y_n\}$ such that $x_i \neq x_j \forall i, j \in [1, n]$ and $y_i \neq y_j \forall i, j \in [1, n]$. $\mathcal{A}$ sends $\mathcal{O}_1(i)$ and $\mathcal{O}_2(i)$ to c_i where $\mathcal{O}_j(i)$ is the i^{th} item in $\mathcal{O}_j$.
   (b) On the basis of a fairly selected bit b, the clients query for the items in $\mathcal{O}_b$.
   (c) Observing the queries in Step 2, $\mathcal{A}$ outputs bit $b^{'}$
   (d) $\mathcal{A}$ wins the round iff. $b^{'} = b$.
2. $\mathcal{A}$ wins the security game iff. she can win any round with non-negligible advantage over random guessing where non-negligibility is defined over an implementation specific security parameter.

The above security game straightforwardly ensures that $\mathcal{A}$ can win a round with non-negligible advantage over guessing if she can distinguish between two sequence of concurrent accesses. Therefore, a mechanism that satifies the game ensures that an adversary cannot correlate items concurrently accessed in the same round.

Further, consider three randomly chosen sets of item $\mathcal{O}_1$, $\mathcal{O}_2$ and $\mathcal{O}_1$. In three successive rounds, $\mathcal{A}$ provides the following sets of items to $\mathcal{C}$:

- Round1: $\mathcal{O}_1$ and $\mathcal{O}_2$
- Round2: $\mathcal{O}_1$ and $\mathcal{O}_3$

In this case, if $\mathcal{C}$ queries for $\mathcal{O}_1$ both in round 1 and 2, and $\mathcal{A}$ could correlate accesses in the current round with previous rounds, $\mathcal{A}$ can win round 2 with non-negligible advantage. Therefore, a mechanism that satisfies the game also ensures that an adversary cannot correlate accesses in successive rounds.

4. OVERVIEW

ConcurORAM stores the position map entries in PD-ORAM and the data blocks in a RingORAM on the server. The stash for the RingORAM (which holds blocks that overflow from the RingORAM tree) is also stored on the server. Since, the stash can grow (and shrink) dynamically after an eviction, this allows the server to learn how many blocks have been evicted to the tree during the eviction. Therefore, to prevent this ConcurORAM allocates a fixed size to the stash which is the maximum size of the stash determined by the experimental upper bound in [15].

Position map. Each position map entry is indexed by a logical block ID and contains the corresponding leaf ID in the RingORAM tree to which that data block is mapped, or indicates that the block is in the stash. Since each level of PD-ORAM contains multiple fixed-sized buckets, an entry

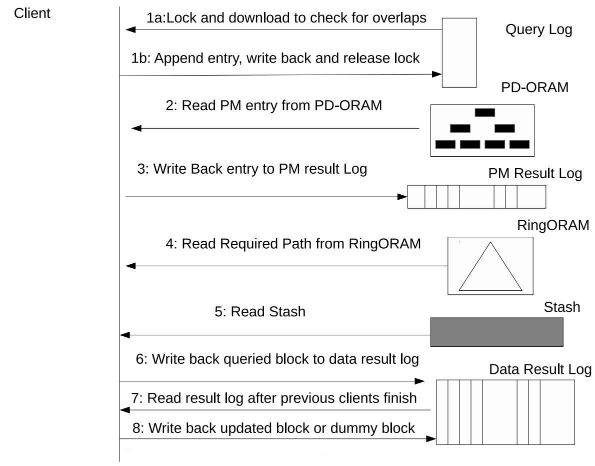

Figure 1: Overview of a query. Clients need to lock only in step 1. Steps 2-6 can proceed concurrently. In step 7, clients wait for previous clients to finish before downloading data result log

for a particular logical block ID if it exists in a PD-ORAM level, is located in the bucket determined by applying the secret hash function for that level on the logical block ID. Clients query for a position map item by downloading the corresponding buckets from each level of the PD-ORAM as determined by the hash function for that level. Further, the top level of the PD-ORAM contains as many entries as the size of the stash. This ensures that during an eviction if the entire stash is evicted to the tree, the entries for these blocks can be added to the top level of PD-ORAM.

In addition, the server maintains three append-only logs: query log, position map (PM) result log and data result log. The logs are stored encrypted on the server.

Query log. The query log records all currently ongoing transactions. Clients download the query log and append the logical ID of the data block they are querying for. In the case where the required data block is already being accessed by another client (and there is a previous entry in the query log for the same), a client accesses a randomly selected data block and updates the query log with its ID. ConcurORAM enforces a lock on the query log during a client access. This prevents a race condition and ensures that all clients have the same consistent view of ongoing transactions.

PM result log. The PM result log contains items that have been accessed from the position map in the last round of concurrent accesses. After reading an item from the position map, a client reencrypts and return the item to the server which is appended to the PM result log.

Data result log. The data result log contains the data blocks that have been accessed from the RingORAM in the last round of concurrent accesses. After finding the required block from either the requested path in the RingORAM tree or the stash, a client reencrypts and return the item to the server which is appended to the data result log.

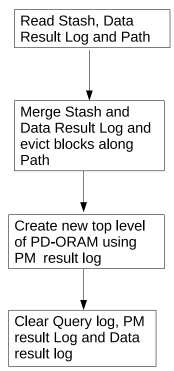

Figure 2: High level description of the eviction process. The path to be evicted is chosen in the reverse lexicographical order.

Figure 1 shows the query protocol for ConcurORAM . Queries proceed as follows:

1. In step 1a and step 1b, a client downloads the query log and appends the logical block ID of the block the client is querying for. If the required block is already being accessed, the client appends the logical block ID of a randomly selected block and queries for the same. During step 1, the server enforces a lock on the query log.
2. In step 2, the client reads a bucket from each level of PD-ORAM to locate the position map entry for the required logical block ID. The PD-ORAM access protocol ensures that the client finds the required position map entry in this step.
3. In step 3, the client reencrypts and writes back the actual position map entry read in Step 2 to the PM result log.
4. In step 4 and 5, the client reads the path on which the queried block exists (as determined from the position map entry) and the stash.
5. In step 6, the client writes back the queried block to data result log.
6. In step 7, the client reads the data result log after all previous clients finish. If a client has executed a random query, the client gets the required block from the data result log.
7. If a client found the required block in step 7, the client writes back the updated value of the block to the data result log for a write access. Otherwise, a client writes back a dummy block.

Note that in step 7, a client finds the most updated version of the required block after all previous ongoing transactions accessing the block has completed.

Eviction. After a fixed number of accesses, the logs are cleared through an eviction to the RingORAM tree (Figure 2). More specifically, after k (a fixed parameter) concurrent queries, the client with the last query reads the logs, the stash and a predetermined path from the RingORAM tree (chosen in the reverse lexicographical order) and tries to evict blocks in the data result log and the stash to the path. First, the data result log and the stash is merged and evicted to the path. Since, there may be multiple compies of the same block in the data result log due to accesses for the same block, only the latest copy of a block in the data result log is merged with the stash and the rest of the copies are discarded. The overflow from the eviction form the new stash. Then, the client creates the new top level of PD-ORAM with the new mappings for the evicted blocks. Since, the top level is of fixed size and the number of blocks evicted is variable, the client adds "fake" entries to ensure that the new top level is of the same size irrespective of the outcome of the eviction. This is similar to Privatefs [21], where the result log becomes the top level of PD-ORAM after a fixed number of accesses.

Further, all the logs are cleared after the eviction. The server maintains an access counter to ensure that the eviction takes place after a fixed number of concurrent accesses. During the eviction, client accesses are stopped to ensure consistency.

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