

# Aquareum: A Centralized Ledger Enhanced with Blockchain and Trusted Computing

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## ABSTRACT

Distributed ledger systems (i.e., blockchains) have received a lot of attention recently. They promise to enable mutually untrusted participants to execute transactions, while providing the immutability of the transaction history and censorship resistance. Although decentralized ledgers may become a disruptive innovation, as of today, they suffer from scalability, privacy, or governance issues. Therefore, they are inapplicable for many important use cases, where interestingly, centralized ledger systems quietly gain adoption and find new use cases. Unfortunately, centralized ledgers have also several drawbacks, like a lack of efficient verifiability or a higher risk of censorship and equivocation.

In this paper, we present Aquareum, a novel framework for centralized ledgers removing their main limitations. By combining a trusted execution environment with a public blockchain platform, Aquareum provides publicly verifiable, non-equivocating, censorship-evident, private, and high-performance ledgers. Aquareum ledgers are integrated with a Turing-complete virtual machine, allowing arbitrary transaction processing logics, including tokens or client-specified smart contracts. Aquareum is fully implemented and deployment-ready, even with currently existing technologies.

## 1 INTRODUCTION

Ledger systems are append-only databases providing immutability (i.e., tamper resistance) as a core property. To facilitate their append-only feature, cryptographic constructions, such as hash chains or hash trees, are usually deployed. Traditionally, public ledger systems are centralized, controlled by a single entity that acts as a trusted party. In such a setting, ledgers are being deployed in various applications, including payments, logging, timestamping services, repositories, or public logs of various artifacts (e.g., keys [6, 33], certificates issued by authorities [29], and binaries [17]).

Although being successfully deployed and envisioned for multiple novel use cases, centralized ledgers have some fundamental limitations due to their centralization. Firstly, they lack efficient verifiability, which would ensure their clients that the ledger is indeed append-only and internally consistent (i.e., does not contain conflicting transactions). A naive solution is just to publish the ledger or share it with parties interested in auditing it, which, however, may be inefficient or stand against the ledger operator’s deployment models (e.g., the privacy of the clients conducting financial transactions can be violated). Second, it is challenging to provide non-equivocation to centralized systems [31]. In simple yet devastating fork attacks, a ledger operator creates two conflicting copies of the ledger and presents it to different clients. Although the forked ledgers are internally consistent, the “global” view of the

database is equivocated, thus completely undermining the security of the entire system. Finally, centralized systems are inherently prone to censorship. A ledger operator can refuse any request or a transaction at her will without leaving any evidence of censoring. This may be risky especially when a censored client may suffer from some consequences (e.g., fines when being unable to settle a transaction on time) or in the case when the operator wishes to hide some ledger content (e.g., data proving her misbehavior). On the other hand, recently emerged public distributed ledgers combine an append-only cryptographic data structure with a consensus algorithm, spreading trust across all participating consensus nodes. These systems are by design publicly verifiable, non-equivocating, and censorship resistant. However, they offer a low throughput, they are expensive in deployment, they do not inherently provide privacy, and their public nature makes their governance difficult and unacceptable for many applications.

**Proposed Approach.** In this paper, we propose Aquareum, a framework for centralized ledgers mitigating their main limitations. Aquareum employs trusted execution environment (TEE) and a public smart contract platform (i.e., built on a blockchain) to provide verifiability, non-equivocation, and to mitigate censorship. In Aquareum, a ledger operator deploys a pre-defined TEE enclave code, which verifies the consistency and correctness of the ledger for every ledger update. Then, a proof produced by the enclave is published utilizing an existing public smart contract platform, guaranteeing that the given snapshot of the ledger is verified and no alternative snapshot of this ledger exists. Furthermore, whenever a client suspects that her query (or transaction) is censored, she can (confidentially) request a resolution of the query via the smart contract platform. The ledger operator noticing the query is obligated to handle it. She passes the query to the enclave that creates a public proof of query resolution and publishes it using the smart contract platform. With such a censorship-evident design, an operator is publicly visible when misbehaving, thus the clients can take appropriate actions (e.g., suing the operator) or encode some automated service-level agreements into their smart contracts.

Aquareum can be adjusted to different ledgers and use cases, but we implemented and deployed it with minimized Ethereum Virtual Machine (EVM) since EVM provides a Turing-complete execution environment and it is widely adopted in the community of decentralized applications. Aquareum enables hosting and execution of arbitrary ledger applications, such as key:value databases, tokens, or client-defined smart contracts, while preserving the same enclave code for verification. Aquareum is fully implemented and we show that it is practical and efficient, even when built using the current technologies and tools.

## 2 BACKGROUND

### 2.1 Blockchain and Smart Contracts

A blockchain (a.k.a., a distributed ledger) is an append-only data structure that is resistant by design against modifications combined with a consensus protocol. In a blockchain, blocks containing data records are linked using a cryptographic hash function, and each new block has to be agreed upon by participants running a consensus protocol (i.e., *consensus nodes*). Each block may contain data records representing orders that transfer crypto-tokens, application codes written in a platform-supported language, and the execution orders of such application codes. These application codes are referred to as *smart contracts*, and they encode arbitrary processing logic (e.g., agreements) written in a supported language of a smart contract platform. Interactions between clients and the smart contract platform are based on messages called *transactions*, which can contain either orders transferring crypto-tokens or calls of smart contract functions. All transactions sent to a blockchain are validated by consensus nodes who maintain a replicated state of the blockchain. To incentivize consensus nodes, blockchain platforms introduce reward and fee schemes.

### 2.2 Trusted Execution Environment

Trusted Execution Environment (TEE) is a hardware-based component that can securely execute arbitrary code in an isolated environment. TEE uses cryptography primitives and hardware-embedded secrets that protect data confidentiality and the integrity of computations. In particular, the adversary model of TEE usually includes privileged applications and an operating system, which may compromise unprivileged user-space applications. There are several practical instances of TEE, such as Intel Software Guard Extensions (SGX) [1, 23, 32] available at Intel’s CPUs or based on RISC-V architecture such as Keystone-enclave [15] and Sanctum [11]. In the context of this work, we built on top of Intel SGX, therefore we adopt the terminology introduced by it.

Intel SGX is a set of instructions that ensures hardware-level isolation of protected user-space codes called *enclaves*. An enclave process cannot execute system calls but can read and write memory outside the enclave. Thus isolated execution in SGX may be viewed as an ideal model in which a process is guaranteed to be executed correctly with ideal confidentiality, while it might run on a potentially malicious operating system.

Intel SGX allows a local process or a remote system to securely communicate with the enclave as well as execute verification of the integrity of the enclave’s code. When an enclave is created, the CPU outputs a report of its initial state, also referred to as a *measurement*, which is signed by the private key of TEE and encrypted by a public key of Intel Attestation Service (IAS). The hardware-protected signature serves as the proof that the measured code is running in an SGX-protected enclave, while the encryption by IAS public key ensures that the SGX-equipped CPU is genuine and was manufactured by Intel. This proof is also known as a *quote* or *attestation*, and it can be verified by a local process or by a remote system. The enclave process-provided public key can be used by a verifier to establish a secure channel with the enclave or to verify the signature during the attestation. We assume that a trustworthy

measurement of the enclave’s code is available for any client that wishes to verify an attestation.

### 2.3 Merkle Tree

A Merkle tree [34] is a data structure based on the binary tree in which each leaf node contains a hash of a single data block, while each non-leaf node contains a hash of its concatenated children. At the top of a Merkle tree is the root hash, which provides a tamper-evident summary of the contents. A Merkle tree enables efficient verification as to whether some data are associated with a leaf node by comparing the expected root hash of a tree with the one computed from a hash of the data in the query and the remaining nodes required to reconstruct the root hash (i.e., *proof* or *authentication path*). The reconstruction of the root hash has the logarithmic time and space complexity, which makes the Merkle tree an efficient scheme for membership verification. To provide a membership verification of element  $x_i$  in the list of elements  $X = \{x_i, i \geq 1\}$ , the Merkle tree supports the following operations:

**MkRoot**( $X$ )  $\rightarrow$  **Root**: an aggregation of all elements of the list  $X$  by a Merkle tree, providing a single value *Root*.

**MkProof**( $x_i, X$ )  $\rightarrow \pi^{\text{mk}}$ : a Merkle proof generation for the  $i$ th element  $x_i$  present in the list of all elements  $X$ .

$\pi^{\text{mk}}$ .**Verify**( $x_i, \text{Root}$ )  $\rightarrow \{\text{True}, \text{False}\}$ : verification of the Merkle proof  $\pi^{\text{mk}}$ , witnessing that  $x_i$  is included in the list  $X$  that is aggregated by the Merkle tree with the root hash *Root*.

### 2.4 History Tree

A Merkle tree has been primarily used for proving membership. However, Crosby and Wallach [12] extended its application for an append-only tamper-evident log, denoted as a *history tree*. A history tree is the Merkle tree, in which leaf nodes are added in an append-only fashion, and which allows to produce logarithmic proofs witnessing that arbitrary two versions of the tree are consistent (i.e., one version of the tree is an extension of another). Therefore, once added, a leaf node cannot be modified or removed.

A history tree brings a versioned computation of hashes over the Merkle tree, enabling to prove that different versions (i.e., commitments) of a log, with distinct root hashes, make consistent claims about the past. To provide a tamper-evident history system [12], the log represented by the history tree  $L$  supports the following operations:

**L.add**( $x$ )  $\rightarrow C_j$ : appending of the record  $x$  to  $L$ , returning a new commitment  $C_j$  that represents the most recent value of the root hash of the history tree.

**L.IncProof**( $C_i, C_j$ )  $\rightarrow \pi^{\text{inc}}$ : an incremental proof generation between two commitments  $C_i$  and  $C_j$ , where  $i \leq j$ .

**L.MemProof**( $i, C_j$ )  $\rightarrow \pi^{\text{mem}}$ : a membership proof generation for the record  $x_i$  from the commitment  $C_j$ , where  $i \leq j$ .

$\pi^{\text{inc}}$ .**Verify**( $C_i, C_j$ )  $\rightarrow \{\text{True}, \text{False}\}$ : verification of the incremental proof  $\pi^{\text{inc}}$ , witnessing that the commitment  $C_j$  contains the same history of records  $x_k, k \in \{0, \dots, i\}$  as the commitment  $C_i$ , where  $i \leq j$ .

$\pi^{\text{mem}}$ .**Verify**( $i, x_i, C_j$ )  $\rightarrow \{\text{True}, \text{False}\}$ : verification of the membership proof  $\pi^{\text{mem}}$ , witnessing that  $x_i$  is the  $i$ th record in the  $j$ th version of  $L$ , fixed by the commitment  $C_j, i \leq j$ .

$\pi^{\text{inc}}.\text{DeriveNewRoot}() \rightarrow C_j$ : a reconstruction of the commitment  $C_j$  from the incremental proof  $\pi^{\text{inc}}$  that was generated by  $L.\text{IncProof}(C_i, C_j)$ .

$\pi^{\text{inc}}.\text{DeriveOldRoot}() \rightarrow C_i$ : a reconstruction of the commitment  $C_i$  from the incremental proof  $\pi^{\text{inc}}$  that was generated by  $L.\text{IncProof}(C_i, C_j)$ .

## 2.5 Radix and Merkle-Patricia Tries

Radix trie serves as a key-value storage. In the Radix trie, every node at the  $l$ -th layer of the trie has the form of  $\langle(p_0, p_1, \dots, p_n), v\rangle$ , where  $v$  is a stored value and all  $p_i$ ,  $i \in \{0, 1, \dots, n\}$  represent the pointers on the nodes in the next (lower) layer  $l + 1$  of the trie, which is selected by following the  $(l + 1)$ -th item of the key. Note that key consists of an arbitrary number of items that belong to an alphabet with  $n$  symbols (e.g., hex symbols). Hence, each node of the Radix trie has  $n$  children and to access a leaf node (i.e., data  $v$ ), one must descend the trie starting from the root node while following the items of the key one-by-one. Note that Radix trie requires underlying database of key-value storage that maps pointers to nodes. However, Radix trie does not contain integrity protection, and when its key is too long (e.g., hash value), the Radix trie will be sparse, thus imposing a high overhead for storage of all the nodes on the path from the root to values.

Merkle Patricia Trie (MPT) [40, 49] is a combination of the Merkle tree (see Section 2.3) and Radix trie data structures, and similar the Radix Trie, it serves as a key-value data storage. However, in contrast to Radix trie, the pointers are replaced by a cryptographically secure hash of the data in nodes, providing integrity protection. In detail, MPT guarantees integrity by using a cryptographically secure hash of the value for the MPT key as well as for the realization of keys in the underlying database that maps the hashes of nodes to their content; therefore, the hash of the root node of the MPT represents an integrity snapshot of the whole MPT trie. Next, Merkle-Patricia trie introduces the *extension nodes*, due to which, there is no need to keep a dedicated node for each item of the path in the key. The MPT trie  $T$  supports the following operations:

$T.\text{root} \rightarrow \text{Root}$ : accessing the hash of the root node of MPT, which is stored as a key in the underlying database.

$T.\text{add}(k, x) \rightarrow \text{Root}$ : adding the value  $x$  with the key  $k$  to  $T$  while obtaining the new hash value of the root node.

$T.\text{get}(k) \rightarrow \{x, \perp\}$ : fetching a value  $x$  that corresponds to key  $k$ ; return  $\perp$  if no such value exists.

$T.\text{delete}(k) \rightarrow \{\text{True}, \text{False}\}$ : deleting the entry with key equal to  $k$ , returning *True* upon success, *False* otherwise.

$T.\text{MptProof}(k) \rightarrow \{\pi^{\text{mpt}}, \overline{\pi^{\text{mpt}}}\}$ : a MPT (inclusion / exclusion) proof generation for the entry with key  $k$ .

$\pi^{\text{mpt}}.\text{Verify}(k, \text{Root}) \rightarrow \{\text{True}, \text{False}\}$ : verification of the MPT proof  $\pi^{\text{mpt}}$ , witnessing that entry with the key  $k$  is in the MPT whose hash of the root node is equal to  $\text{Root}$ .

$\overline{\pi^{\text{mpt}}}.\text{VerifyNeg}(k, \text{Root}) \rightarrow \{\text{True}, \text{False}\}$ : verification of the negative MPT proof, witnessing that entry with the key  $k$  is not in the MPT with the root hash equal to  $\text{Root}$ .

## 2.6 Notation

The notation used throughout the paper is presented in the following. By  $\{msg\}_{\mathbb{U}}$ , we denote the message  $msg$  digitally signed by

$\mathbb{U}$ , and by  $msg.\sigma$  we refer to a signature;  $h(\cdot)$  stands for a cryptographic hash function;  $\parallel$  is the string concatenation;  $\%$  represents modulo operation over integers;  $\Sigma_p.\{KeyGen, Verify, Sign\}$  represents a signature (and encryption) scheme of the platform  $p$ , where  $p \in \{pb, tee\}$  (i.e., public blockchain platform and trusted execution environment platform); and  $SK_{\mathbb{U}}^p, PK_{\mathbb{U}}^p$  is the private/public key-pair of  $\mathbb{U}$ , under  $\Sigma_p$ . Then, we use  $\pi^s$  for denoting proofs of various data structures  $s \in \{mk, mem, inc\}$ :  $\pi^{mk}$  denotes the inclusion proof in the Merkle tree,  $\pi^{mem}$  and  $\pi^{inc}$  denote the membership proof and the incremental proof in the history tree, respectively.

## 3 SYSTEM MODEL AND OVERVIEW

### 3.1 System Model

In Aquareum, an *operator* is an entity that maintains and manages a ledger containing chronologically sorted transactions. *Clients* interact with the ledger by sending requests, such as queries and transactions to be handled. We assume that all involved parties can interact with a blockchain platform supporting smart contracts (e.g., Ethereum). Next, we assume that the operator has access to a TEE platform (e.g., Intel SGX). Finally, we assume that the operator can be malicious and her goals are as follows:

**Violation of the ledger's integrity** by creating its internal inconsistent state – e.g., via inserting two conflicting transactions or by removing/modifying existing transactions.

**Equivocation of the ledger** by presenting at least two inconsistent views of the ledger to (at least) two distinct clients who would accept such views as valid.

**Censorship of client queries** without leaving any audit trails evincing the censorship occurrence.

Next, we assume that the adversary cannot undermine the cryptographic primitives used, the underlying blockchain platform, and the TEE platform deployed.

### 3.2 Desired Properties

We target the following security properties for Aquareum ledgers:

**Verifiability**: clients should be able to obtain easily verifiable evidence that the ledger they interact with is internally *correct* and *consistent*. In particular, it means that none of the previously inserted transaction was neither modified nor deleted, and there are no conflicting transactions. Traditionally, the verifiability is achieved by replicating the ledger (like in blockchains) or by trusted auditors who download the full copy of the ledger and sequentially validate it. However, this property should be provided even if the operator does not wish to share the full database with third parties. Besides, the system should be *self-auditable*, such that any client can easily verify (and prove to others) that some transaction is included in the ledger, and she can prove the state of the ledger at the given point in time.

**Non-Equivocation**: the system should protect from forking attacks and thus guarantee that no concurrent (equivocating) versions of the ledger exist at any point in time. The consequence of this property is that whenever a client interacts with the ledger or relies on the ledger's logged artifacts, the client is ensured that other clients have ledger views consistent with her view.

**Censorship Evidence:** preventing censorship in a centralized system is particularly challenging, as its operator can simply pretend unavailability in order to censor undesired queries or transactions. However, this property requires that whenever the operator censors client’s requests, the client can do a resolution of an arbitrary (i.e., censored) request publicly. We emphasize that proving censorship is a non-trivial task since it is difficult to distinguish “pretended” unavailability from “genuine” one. Genuine censorship evidence enables clients to enforce potential service-level agreements with the operator, either by a legal dispute or by automated rules encoded in smart contracts.

Besides those properties, we intend the system to provide *privacy* (keeping the clients’ communication confidential), *efficiency* and *high performance*, not introducing any significant overhead, *deployability* with today’s technologies and infrastructures, as well as *flexibility* enabling various applications and scenarios.

### 3.3 High-Level Overview

Aquareum ledger is initialized by an operator ( $\textcircled{O}$ ) who creates an internal ledger ( $L$ ) that will store all transactions processed and the state that they render. Initially,  $L$  contains an empty transaction set and a null state. During the initialization,  $\textcircled{O}$  creates a TEE enclave ( $\textcircled{E}$ ) whose role is to execute updates of  $L$  and verify consistency of  $L$  before each update. Initialization of  $\textcircled{E}$  involves the generation of two public private key pairs – one for the signature scheme of TEE (i.e.,  $PK_{\textcircled{E}}^{tee}, SK_{\textcircled{E}}^{tee}$ ) and one for the signature scheme of the public blockchain (i.e.,  $PK_{\textcircled{E}}^{pb}, SK_{\textcircled{E}}^{pb}$ ).<sup>1</sup> The code of  $\textcircled{E}$  is publicly-known (see Algorithm 1 and Algorithm 6), and it can be remotely attested with the TEE infrastructure by any client.

Next,  $\textcircled{O}$  generates her public-private key pair (i.e.,  $PK_{\textcircled{O}}, SK_{\textcircled{O}}$ ) and deploys a special smart contract ( $\textcircled{S}$ ) initialized with the empty  $L$  represented by its hash  $LHash$ , the operator’s public key  $PK_{\textcircled{O}}$ , and both enclave public keys  $PK_{\textcircled{E}}^{tee}$  and  $PK_{\textcircled{E}}^{pb}$ . After the deployment of  $\textcircled{S}$ , an instance of  $L$  is uniquely identified by the address of  $\textcircled{S}$ . A client ( $\textcircled{C}$ ) wishing to interact with  $L$  obtains the address of  $\textcircled{S}$  and performs the remote attestation of  $\textcircled{E}$  using the  $PK_{\textcircled{E}}^{tee}$ .

Whenever  $\textcircled{C}$  sends a transaction to  $\textcircled{O}$  (see Figure 1),  $\textcircled{E}$  validates whether it is authentic and non-conflicting; and if so,  $\textcircled{E}$  updates  $L$  with the transaction, yielding the new version of  $L$ . The  $\textcircled{C}$  is responded with a *receipt* and “a version transition of  $L$ ”, both signed by  $\textcircled{E}$ , which prove that the transaction was processed successfully and is included in the new version of  $L$ . For efficiency reasons, transactions are processed in batches that are referred to as *blocks*. In detail,  $\textcircled{O}$  starts the update procedure of  $L$  (see Figure 1) as follows:

- a)  $\textcircled{O}$  sends all received transactions since the previous update to  $\textcircled{E}$ , together with the current partial state of  $L$  and a small subset of  $L$ ’s data  $\partial L_i$ , such that  $h(\partial L_i) = h(L_i)$ , which is required to validate  $L$ ’s consistency and perform its incremental extension.
- b)  $\textcircled{E}$  validates and executes the transactions in its virtual machine, updates the current partial state and partial data of  $L$ , and finally creates a blockchain transaction<sup>2</sup>  $\{h(\partial L_i), h(\partial L_{i+1})\}_{\textcircled{E}}$  signed by  $SK_{\textcircled{E}}^{pb}$ , which represents a version transition of the ledger from

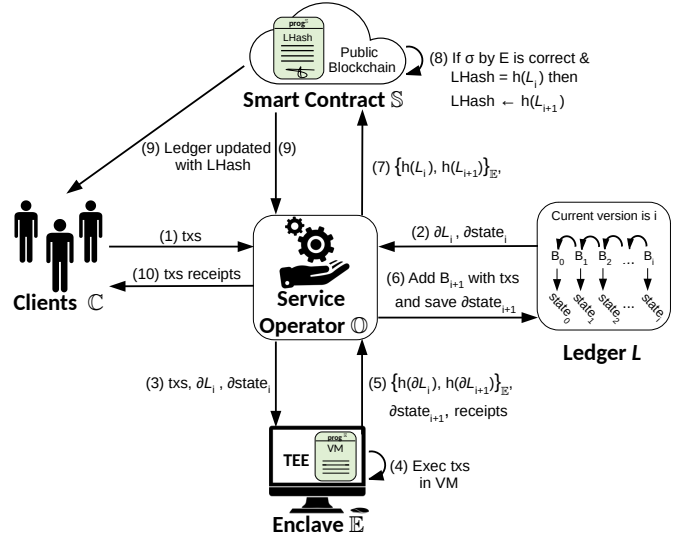


Figure 1: Operation procedure of Aquareum ledger.

version  $i$  to its new version  $i + 1$ , also referred to as the **version transition pair**.

- c) The blockchain transaction with version transition pair is returned to  $\textcircled{O}$ , who sends this transaction to  $\textcircled{S}$ .
- d)  $\textcircled{S}$  accepts the second item of the version transition pair as the current hash of  $L$  iff it is signed by  $SK_{\textcircled{E}}^{pb}$  and the current hash of  $L$  stored by  $\textcircled{S}$  (i.e.,  $LHash$ ) is equal to the first item of the pair.

After the update of  $L$  is finished, clients with receipts obtained can verify that their transactions were processed by  $\textcircled{E}$  (see details in Section 4.3). The update procedure ensures that the new version of  $L$  is: (1) **internally correct** since it was executed by trusted code of  $\textcircled{E}$ , (2) a **consistent** extension of the previous version – relying on trusted code of  $\textcircled{E}$  and a witnessed version transition by  $\textcircled{S}$ , and (3) **non-equivocating** since  $\textcircled{S}$  stores only hash of a single version of  $L$  (i.e.,  $LHash$ ) at any point in time.

Whenever  $\textcircled{C}$  suspects that her transactions or read queries are censored,  $\textcircled{C}$  might send such requests via  $\textcircled{S}$  (see details in Section 4.4 and Section 4.5). To do so,  $\textcircled{C}$  encrypts her request with  $PK_{\textcircled{E}}^{pb}$  and publishes it on the blockchain via  $\textcircled{S}$ .  $\textcircled{O}$  noticing a new request is obligated to pass the request to  $\textcircled{E}$ , which will process the request and reply with an encrypted response (by  $PK_{\textcircled{C}}^{pb}$ ) that is processed by  $\textcircled{S}$ . If a pending request at  $\textcircled{S}$  is not handled by  $\textcircled{O}$ , it is public evidence that  $\textcircled{O}$  censors the request. We do not specify how can  $\textcircled{C}$  utilize such a proof, but it could be shown in a potential legal dispute or  $\textcircled{S}$  itself could have an automated deposit-based punishments rules.

### 3.4 Design Consideration

We might design  $L$  as an append-only chain (as in blockchains), but such a design would bring a high overhead on clients who want to verify that a particular block is a part of  $L$ . During the verification, clients would have to download the headers of all blocks between the head of  $L$  and the block in the query, resulting into linear space & time complexity. In contrast, when a history tree (see Section 2.4) is utilized for integrity preservation of  $L$ , the presence of any block in  $L$  can be verified with logarithmic space and time complexity.

<sup>1</sup>Note that neither of the private keys ever leaves  $\textcircled{E}$ .

<sup>2</sup>Note that  $\{h(\partial L_i), h(\partial L_{i+1})\}_{\textcircled{E}} = \{h(L_i), h(L_{i+1})\}_{\textcircled{E}}$

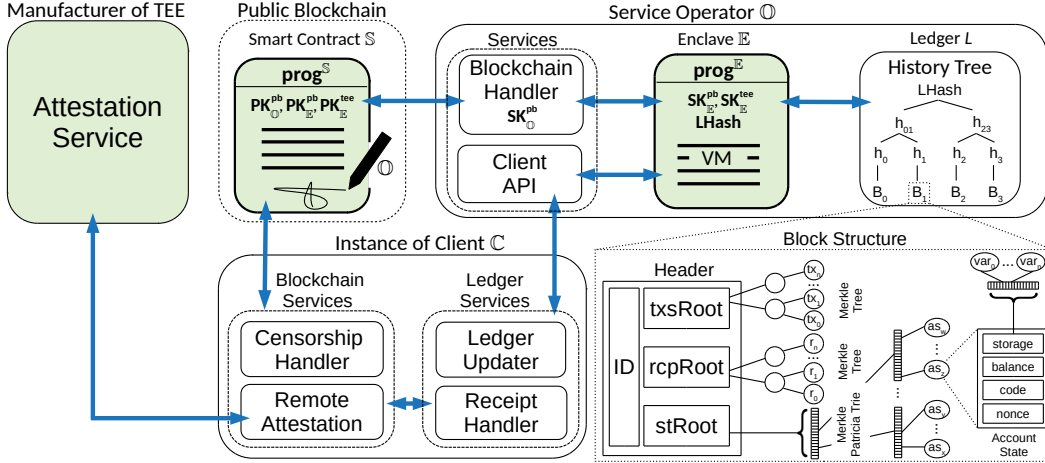


Figure 2: Aquareum components. Trusted components are depicted in green.

## 4 DETAILS

The schematic overview of Aquareum is depicted in Figure 2, where trusted components are depicted in green. The right part of the figure describes data aggregation of  $L$ . We utilize a history tree [12] for tamper-evident logging of data blocks due to its efficient membership and incremental proofs (see Section 3.4). The aggregation of blocks within a history tree is represented by root hash  $LRoot$ , which instantiates ledger hash  $LHash$  from Section 3.3. In Aquareum, each data block consists of a header, a list of transactions, and a list of execution receipts from VM that is running within  $\mathbb{E}$ . A header contains the following fields:

- **ID**: this field is assigned for each newly created block as a counter of all blocks. ID of each block represents the  $ID$ th version of the history tree of  $L$ , which contains blocks  $B_0, \dots, B_{ID-1}$  and is characterized by the root hash  $r \leftarrow MkRoot(\{H_0, \dots, H_{ID-1}\})$ , where  $H_i$  stands for a header of a block  $B_i$ . Note that the  $ID$ th version of  $L$  with the root hash  $r$  can also be expressed by the notation  $\#(r)$ .
- **txsRoot, rcpRoot**: two root hash values that aggregate set of transactions and the set of their corresponding execution receipts (containing execution logs) by Merkle trees [34],
- **stRoot**: the root hash that aggregates the current global state of the virtual machine by Merkle-Patricia trie [40, 49]. In detail, MPT aggregates all account states into a global state, where keys of MPT represent IDs of client accounts (i.e.,  $h(PK_C^{pb})$ ) and values represent an account state data structures, which (similar to [49]) contains: (1) *balance* of a native token (if any), (2) *code* that is executed when an account receives a transaction; accounts with no code represent simple accounts and accounts with a code field represent smart contract accounts, (3) *nonce* represents the number of transactions sent from the simple account or the number of contracts created by the smart contract account, (4) *storage* represents encoded variables of a smart contract, which can be realized by Merkle-Patricia trie [40, 49] or other integrity-preserving mapping structures.

Although  $\mathbb{O}$  persists the full content of  $L$  (and maintains its full state in the memory), she is unable to directly modify  $L$  while remaining undetected since all modifications of  $L$  must be done through  $\mathbb{E}$ . In

detail, upon receiving enough transactions from clients,  $\mathbb{E}$  executes received transactions by its virtual machine (VM) and updates  $L$  accordingly. While updating  $L$ ,  $\mathbb{E}$  leverages the incremental proofs of the history tree to ensure integrity and consistency with the past versions of  $L$ .

The enclave  $\mathbb{E}$  in our approach stores the last produced header ( $hdr_{last}$ ) and the current root hash of the history tree of  $L$  (i.e.,  $LRoot$ ), which enables  $\mathbb{E}$  to make extensions of  $L$  that are consistent with  $L$ 's history and at the same time avoiding dishonest  $\mathbb{O}$  to tamper with  $L$ . Although state-fullness of  $\mathbb{E}$  might be seen as a limitation in the case of a failed enclave, we show how to deal with this situation and provide a procedure that publicly replaces a failed enclave using  $\mathbb{S}$  (see Section 4.6).

### 4.1 Setup

The setup of Aquareum is presented in Figure 3.<sup>3</sup> First,  $\mathbb{O}$  initializes an empty  $L$ , a root hash  $LRoot_{cur}$  for the most recent local version of  $L$ , the root hash  $LRoot_{pb}$  for the version synchronized with PB, the empty global state of  $L$ , and the empty list of reported censored requests. Then,  $\mathbb{O}$  initializes  $\mathbb{E}$  with code  $prog^{\mathbb{E}}$  (see Algorithm 1). In this initialization,  $\mathbb{E}$  generates two key-pairs,  $SK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}$  and  $SK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{tee}$ , respectively; the first key-pair is intended for interaction with the blockchain platform and the second one is intended for the remote attestation with TEE infrastructure. Next,  $\mathbb{E}$  initializes  $L$  and two root hashes in the same vein as  $\mathbb{O}$  did. In addition,  $\mathbb{E}$  stores the header  $hdr_{cur}$  of the last block created and signed by  $\mathbb{E}$  and its ID. Then,  $\mathbb{E}$  sends its public keys  $PK_{\mathbb{E}}^{pb}$  and  $PK_{\mathbb{E}}^{tee}$  to  $\mathbb{O}$ . Next,  $\mathbb{O}$  creates a deployment transaction of  $\mathbb{S}$ 's code  $prog^{\mathbb{S}}$  (see Algorithm 2) with public keys  $PK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{tee}, PK_{\mathbb{O}}$  as the arguments (see Algorithm 4 in Appendix for pseudo-code of  $\mathbb{O}$ ). Then,  $\mathbb{O}$  sends the deployment transaction to the blockchain. In the constructor of  $\mathbb{S}$ , all public keys are stored, and the root hash of  $L$  with the list of censored requests are initialized. Finally,  $\mathbb{S}$  publishes its identifier  $\mathbb{S}^{ID}$ , which serves as a public reference to  $\mathbb{S}$ .

When the infrastructure of Aquareum is initialized,  $\mathbb{C}$ 's register at  $\mathbb{O}$ . For simplicity, we omit details of the registration and access control, and we let this up to the discretion of  $\mathbb{O}$ .

<sup>3</sup>We assume that  $\mathbb{O}$  has already generated her public/private key-pair  $PK_{\mathbb{O}}^{pb}, SK_{\mathbb{O}}^{pb}$ .

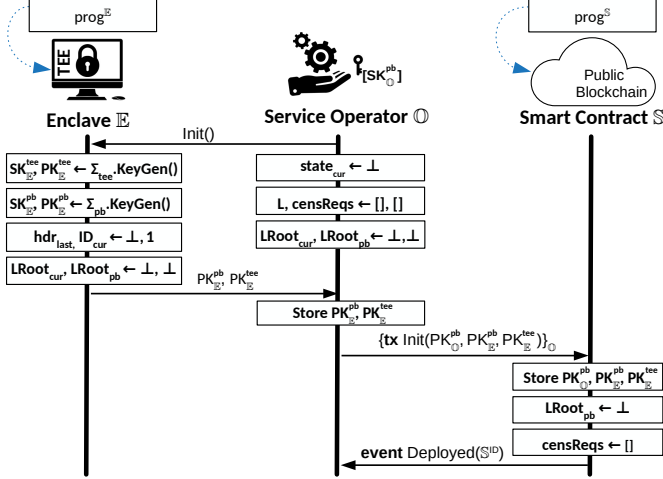


Figure 3: Protocol for setup ( $\Pi_S$ ).

## 4.2 Normal Operation

In the case of normal operation (see Figure 4),  $\mathbb{O}$  is not censoring any transactions produced by instances of  $\mathbb{C}$ , hence all transactions are correctly executed within  $\mathbb{E}$  and appended to  $L$ , while  $\mathbb{S}$  publicly witnesses the correct execution of transactions and the consistency of the new version of  $L$  with its history. In detail, when  $\mathbb{O}$  receives a transaction from  $\mathbb{C}_x$ , it performs access control of  $\mathbb{C}_x$ ,<sup>4</sup> and upon the success,  $\mathbb{O}$  adds the transaction in its cache of unprocessed transactions (see Algorithm 4 in Appendix). When  $\mathbb{O}$  accumulates enough transactions from clients, it passes these transactions to  $\mathbb{E}$ , together with the current partial state  $\delta state_{cur}$  of the VM.

**4.2.1 VM Execution with Partial State.** The current partial state of VM represents only data related to all account states that the execution of transactions is about to modify or create. The motivation for such an approach is the limited memory size of  $\mathbb{E}$  (e.g., in the case of SGX it is only  $\sim 100$ MB), which does not allow to internally store the full global state of  $L$  (neither  $L$  itself). The partial state does not contain only the account states of concerning transactions, but it also contains intermediary nodes of MPT (i.e., extension and branch nodes) that are on the path from the root node of MPT to leaf nodes of concerning account states. Using passed partial state,  $\mathbb{E}$  verifies its integrity, obtains the state root of MPT and compares it with the last known state root (i.e.,  $hdr_{last}.stRoot$ ) produced by  $\mathbb{E}$ . If the roots match,  $\mathbb{E}$  executes transactions using the passed partial state, obtains the new partial state of VM and execution receipts with additional information about the execution of particular transactions (i.e., return codes and logs). Note that  $\mathbb{E}$  obtains the new partial state by consecutively updating the current partial state with each transaction executed.

Next,  $\mathbb{E}$  creates the header of the new block (i.e.,  $hdr_{cur}$ ) from aggregated transactions, receipts, and new partial state. Using created header,  $\mathbb{E}$  extends the previous version of the history tree of  $L$ , while obtaining the new root hash  $LRoot_{cur}$  of  $L$  (see Section 4.2.2). Then,  $\mathbb{E}$  signs a version transition pair  $\langle LRoot_{pb}, LRoot_{cur} \rangle$  of the history tree by  $SK_{\mathbb{E}}^{pb}$  and sends it to  $\mathbb{O}$ , together with the new header, the new partial state, and execution receipts. Moreover,  $\mathbb{E}$  stores the

<sup>4</sup>For simplicity, we omit access control at  $\mathbb{O}$ .

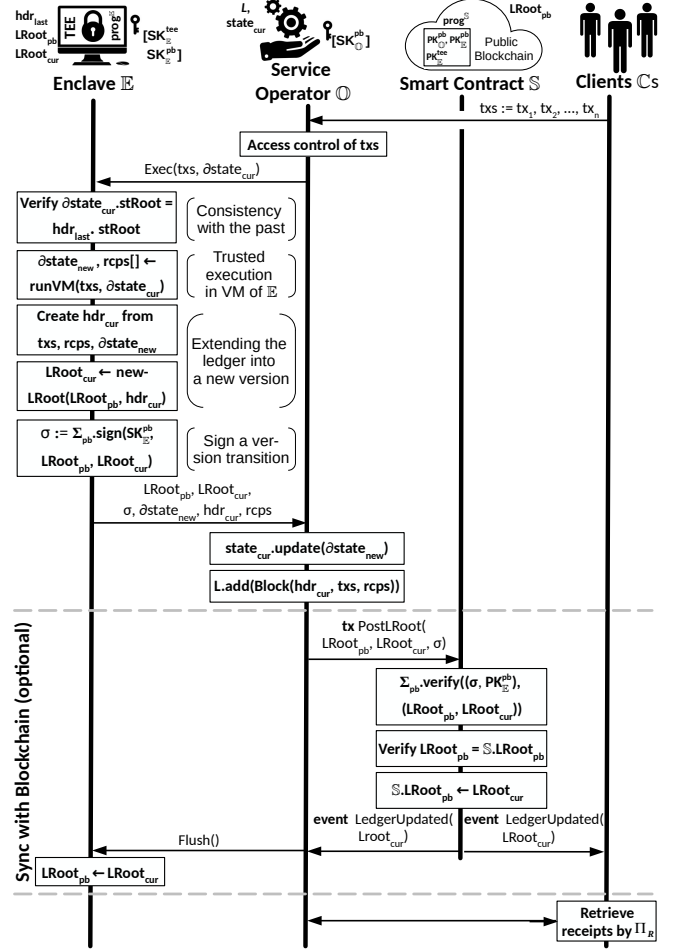


Figure 4: Protocol for normal operation ( $\Pi_N$ ).

last produced header (i.e.,  $hdr_{last}$ ) and the root hash  $LRoot_{cur}$  of  $L$  associated with the last version of the history tree.

**4.2.2 Incremental Update of the Ledger.** We omitted the details about the consistent update of  $L$  within  $\mathbb{E}$  in the above text and Figure 4. In general, an incremental update of a history tree assumes trusted full access to its data. However,  $\mathbb{E}$  does not store full data of  $L$  (only the last header created), and thus cannot directly make a consistent update of  $L$ . Therefore, we design a simple procedure that enables  $\mathbb{E}$  to extend  $L$  without storing it internally.

In the procedure,  $\mathbb{O}$  creates a proof template  $\pi_{next}^{inc}$  for the next incremental proof of the history tree, which extends  $L$  exactly by one empty block (see function  $nextIncProof()$  in Algorithm 4) while obtaining a new version of  $L$  with the (temporary) root hash  $LRoot_{tmp}$ . Note that this template represents  $\partial L$  from Section 3.3, and it enables  $\mathbb{E}$  to make an integrity verification and consistent extension of  $L$  without storing it. In detail,  $\mathbb{O}$  sends  $\pi_{next}^{inc}$  and  $LRoot_{tmp}$  to  $\mathbb{E}$ , together with transactions that are about to be processed by function  $Exec()$ .  $\mathbb{E}$  verifies  $\pi_{next}^{inc}$  with respect to its last known version of  $L$  (i.e.,  $\#(LRoot_{cur})$ ), replaces the header hash of the empty block in the proof template by the hash of newly created header in  $\mathbb{E}$ , and

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**Algorithm 1:** The program  $prog^{\mathbb{E}}$  of enclave  $\mathbb{E}$ 

---

▷ DECLARATION OF TYPES AND FUNCTIONS:  
**Header** {  $ID$ ,  $txsRoot$ ,  $rcpRoot$ ,  $stRoot$ };  
 $\#(r) \rightarrow v$ : denotes the version  $v$  of  $L$  having  $LRoot = r$ ,

▷ VARIABLES OF TEE:  
 $SK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{tee}$ : keypair of  $\mathbb{E}$  under  $\Sigma_{tee}$ ,  
 $SK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}$ : keypair of  $\mathbb{E}$  under  $\Sigma_{pb}$ ,  
 $hdr_{last} \leftarrow \perp$ : the last header created by  $\mathbb{E}$ ,  
 $LRoot_{pb} \leftarrow \perp$ : the last root of  $L$  flushed to PB,  
 $LRoot_{cur} \leftarrow \perp$ : the root of  $L \cup blksp$  (not flushed to PB),  
 $ID_{cur} \leftarrow 1$ : the current version of  $L$  (not flushed to PB),

▷ DECLARATION OF FUNCTIONS:  
**function**  $Init()$  **public**  
     $(SK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}) \leftarrow \Sigma_{pb}.Keygen();$   
     $(SK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{tee}) \leftarrow \Sigma_{tee}.Keygen();$   
    **Output**  $(PK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{pb});$

**function**  $Exec(txS[], \partial st^{old}, \pi_{next}^{inc}, LRoot_{tmp})$  **public**  
    **assert**  $\partial st^{old}.root = hdr_{last}.stRoot;$   
     $\partial st^{new}, rcps, txs_{er} \leftarrow processTxS(txS, \partial st^{old}, \pi_{next}^{inc}, LRoot_{tmp});$   
     $\sigma \leftarrow \Sigma_{pb}.sign(SK_{\mathbb{E}}^{pb}, (LRoot_{pb}, LRoot_{cur}));$   
    **Output**  $(LRoot_{pb}, LRoot_{cur}, \partial st^{new}, hdr_{last}, rcps, txs_{er}, \sigma);$

**function**  $Flush()$  **public**  
     $LRoot_{pb} \leftarrow LRoot_{cur};$  ▷ Shift the version of  $L$  synchronized with PB.

**function**  $processTxS(txS[], \partial st^{old}, \pi_{next}^{inc}, LRoot_{tmp})$  **private**  
     $\partial st^{new}, rcps[], txs_{er} \leftarrow runVM(txS, \partial st^{old});$  ▷ Run  $txS$  in VM.  
     $txS \leftarrow txS \setminus txs_{er};$  ▷ Filter out parsing errors/wrong signatures.  
     $hdr \leftarrow Header(ID_{cur}, MkRoot(txS), MkRoot(rcps), \partial st^{new}.root);$   
     $hdr_{last} \leftarrow hdr;$   
     $ID_{cur} \leftarrow ID_{cur} + 1;$   
     $LRoot_{cur} \leftarrow newLRoot(hdr, \pi_{next}^{inc}, LRoot_{tmp});$   
    **return**  $\partial st^{new}, rcps, txs_{er};$

**function**  $newLRoot(hdr, \pi_{next}^{inc}, LRoot_{tmp})$  **private**  
    ▷ A modification of the incr. proof. template to contain  $hdr$   
    **assert**  $\#(LRoot_{cur}) + 1 = \#(LRoot_{tmp});$  ▷ 1 block  $\Delta$ .  
    **assert**  $\pi_{next}^{inc}.Verify(LRoot_{cur}, LRoot_{tmp});$   
     $\pi_{next}[-1] \leftarrow h(hdr);$   
    **return**  $deriveNewRoot(\pi_{next}^{inc});$

---

then uses such modified proof to compute the new root hash of  $L$ , which is then stored as  $LRoot_{cur}$  by  $\mathbb{E}$ .

When  $\mathbb{O}$  receives the output of  $\mathbb{E}$ , it updates the full state of  $L$  and creates the new block using client transactions, the received receipts, and the header of the new block. Then,  $\mathbb{O}$  appends the new block to  $L$  and responds to client requests for receipts of their transactions (see Section 4.3), which serve as *promises* confirming the execution of transactions. These promises became irreversible when  $\mathbb{O}$  syncs  $L$  with  $\mathbb{S}$  that runs on the blockchain platform.

**4.2.3 Syncing the Ledger with the Blockchain.**  $\mathbb{O}$  periodically syncs  $L$  with  $\mathbb{S}$  to provide non-equivocation of  $L$ . However,  $\mathbb{O}$  is able to sync only such a version of  $L$  that was signed within  $\mathbb{E}$  and is newer than the last known version by  $\mathbb{S}$ , which provides consistency and non-equivocation of  $L$ . During the sync of  $L$ ,  $\mathbb{O}$  creates a special blockchain transaction containing the version transition pair  $(LRoot_{pb}, LRoot_{cur})$  signed within  $\mathbb{E}$  and sends it to  $\mathbb{S}$  (i.e., calling the function  $PostLRoot()$ ).  $\mathbb{S}$  verifies whether the version transition pair was signed within  $\mathbb{E}$  by checking the signature with  $PK_{\mathbb{E}}^{pb}$ . Then,  $\mathbb{S}$  verifies whether the last published version of  $L$  (corresponding to  $LRoot_{pb}$  at  $\mathbb{S}$ ) is equal to the first entry in the version transition pair. In the positive case,  $\mathbb{S}$  publicly performs the version transition of  $L$  by updating its  $LRoot_{pb}$  to the second

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**Algorithm 2:** The program  $prog^{\mathbb{S}}$  of the smart contract  $\mathbb{S}$ 

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▷ DECLARATION OF TYPES AND CONSTANTS:  
**CensInfo** {  $etx$ ,  $equery$ ,  $status$ ,  $edata$  },  
 $msg$ : a current transaction that called  $\mathbb{S}$ ,

▷ DECLARATION OF FUNCTIONS:  
**function**  $Init(PK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{tee}, PK_{\mathbb{O}})$  **public**  
     $PK_{\mathbb{E}}^{tee}[] \mathit{.add}(PK_{\mathbb{E}}^{tee});$  ▷ PK of enclave  $\mathbb{E}$  under  $\Sigma_{tee}$ .  
     $PK_{\mathbb{E}}^{pb}[] \mathit{.add}(PK_{\mathbb{E}}^{pb});$  ▷ PK of enclave  $\mathbb{E}$  under  $\Sigma_{pb}$ .  
     $PK_{\mathbb{O}} \leftarrow PK_{\mathbb{O}};$  ▷ PK of operator  $\mathbb{O}$  under  $\Sigma_{pb}$ .  
     $LRoot_{pb} \leftarrow \perp;$  ▷ The most recent root hash of  $L$  synchronized with  $\mathbb{S}$ .  
     $censReqs \leftarrow [];$  ▷ Request that  $\mathbb{C}$ s wants to resolve publicly.

**function**  $PostLRoot(root_A, root_B, \sigma)$  **public**  
    ▷ Verify whether a state transition was made within  $\mathbb{E}$ .  
    **assert**  $\Sigma_{pb}.verify((\sigma, PK_{\mathbb{E}}^{pb}[-1]), (root_A, root_B));$   
    ▷ Verify whether a version transition extends the last one.  
    **if**  $LRoot_{pb} = root_A$  **then**  
         $LRoot_{pb} \leftarrow root_B;$  ▷ Do a version transition of  $L$ .

**function**  $ReplaceEnc(PKN_{\mathbb{E}}^{pb}, PKN_{\mathbb{E}}^{tee}, r_A, r_B, \sigma, \sigma_{msg})$  **public**  
    ▷ Called by  $\mathbb{O}$  in the case of enclave failure.  
    **assert**  $\Sigma_{pb}.verify((\sigma_{msg}, PK_{\mathbb{O}}), msg);$  ▷ Avoiding MiTM attack.  
     $PostLRoot(r_A, r_B, \sigma);$  ▷ Do a version transition.  
     $PK_{\mathbb{E}}^{tee} \mathit{.add}(PKN_{\mathbb{E}}^{tee});$  ▷ Upon change,  $\mathbb{C}$ s make remote attestation.  
     $PK_{\mathbb{E}}^{pb} \mathit{.add}(PKN_{\mathbb{E}}^{pb});$

**function**  $SubmitCensTx(etx, \sigma_{msg})$  **public**  
    ▷ Called by  $\mathbb{C}$  in the case her TX is censored.  
     $accessControl(\sigma_{msg}, msg.PK_{\mathbb{C}}^{pb});$   
     $censReqs \mathit{.add}(\mathbf{CensInfo}(etx, \perp, \perp, \perp));$

**function**  $ResolveCensTx(idx_{req}, status, \sigma)$  **public**  
    ▷ Called by  $\mathbb{O}$  to prove that  $\mathbb{C}$ 's TX was processed.  
    **assert**  $idx_{req} < |censReqs|;$   
     $r \leftarrow censReqs[idx_{req}];$   
    **assert**  $\Sigma_{pb}.verify((\sigma, PK_{\mathbb{E}}^{pb}[-1]), (h(r.etx), status));$   
     $r.status \leftarrow status;$

**function**  $SubmitCensQry(equery, \sigma_{msg})$  **public**  
    ▷ Called by  $\mathbb{C}$  in the case its read query is censored.  
     $accessControl(\sigma_{msg}, msg.PK_{\mathbb{C}}^{pb});$   
     $censReqs \mathit{.add}(\mathbf{CensInfo}(\perp, equery, \perp, \perp));$

**function**  $ResolveCensQry(idx_{req}, status, edata, \sigma)$  **public**  
    ▷ Called by  $\mathbb{O}$  as a response to the  $\mathbb{C}$ 's censored read query.  
    **assert**  $idx_{req} < |censReqs|;$   
     $r \leftarrow censReqs[idx_{req}];$   
    **assert**  
         $\Sigma_{pb}.verify((\sigma, PK_{\mathbb{E}}^{pb}[-1]), (h(r.equery), status, h(edata)));$   
     $r.\{edata \leftarrow edata, status \leftarrow status\};$

---

item of the version transition pair. From that moment, the Aquareum transactions processed until the current version of  $L$  cannot be tampered with – providing a non-equivocation of  $L$ . Finally,  $\mathbb{O}$  notifies  $\mathbb{E}$  about successful sync by calling function  $Flush()$  (see Algorithm 1), where  $\mathbb{E}$  “shifts”  $LRoot_{pb}$  to  $LRoot_{cur}$ .

Note that if  $\mathbb{O}$  were to sync  $L$  with  $\mathbb{S}$  upon every new block created, it might be too expensive. On the other hand, if  $\mathbb{O}$  were to sync  $L$  to  $\mathbb{S}$  with long delays, “a level” of non-equivocation would be decreased, which in turn would extend the time to finality. Hence, the sync interval must be viewed as a trade-off between costs and a level of non-equivocation (see examples in Section 5.2). The frequency of syncs might be defined in SLA with clients and violation might be penalized by  $\mathbb{S}$ .

### 4.3 Retrieval and Verification of Receipts

Receipt retrieval and verification serves as a lightweight audit procedure in which  $\mathbb{C}$  verifies inclusion and execution of the transaction

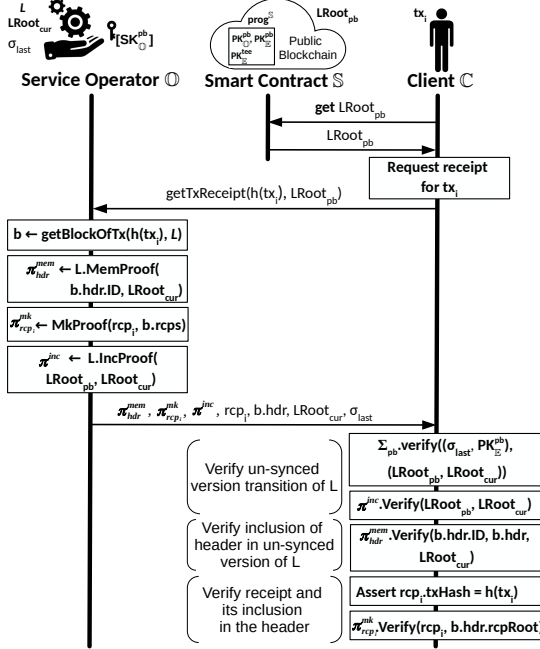


Figure 5: Protocol for receipt retrieval ( $\Pi_R$ ).

$tx_i$  by obtaining its receipt. An execution receipt contains three fields: (1) hash of  $tx_i$ , (2) return code of VM, and (3) log of events emitted by EVM.

To obtain an execution receipt of  $tx_i$ ,  $C$  first retrieves the last root hash of  $L$  (i.e.,  $LRoot_{pb}$ ) from  $S$ . Then,  $C$  requests  $O$  for an inclusion proof of her transaction  $tx_i$  in the most recent version of  $L$  that extends the version  $\#(LRoot_{pb})$ . Upon request,  $O$  finds a block  $b$  that contains  $tx_i$  and computes a membership proof  $\pi_{hdr}^{mem}$  of  $b$ 's header in the most recent version  $\#(LRoot_{cur})$  of  $L$ . The second proof that  $O$  computes is the Merkle proof  $\pi_{rcp}^{mk}$ , which witnesses that receipt  $rcp_i$  of transaction  $tx_i$  is included in the block  $b$ . Then,  $O$  computes the incremental proof  $\pi^{inc}$  of the most recent version transition  $\langle LRoot_{pb}, LRoot_{cur} \rangle$  that was executed within  $E$ . In response,  $O$  sends the following data to  $C$ :

- the receipt  $rcp_i$  with its proof  $\pi_{rcp_i}^{mk}$ ,
- the header of  $b$  with its proof  $\pi_{hdr}^{mem}$ ,
- the most recent version  $LRoot_{cur}$  of  $L$  with its proof  $\pi^{inc}$ ,
- the signature  $\sigma_{last}$  of the most recent version transition  $\langle LRoot_{pb}, LRoot_{cur} \rangle$  made by  $E$ .

$C$  verifies the signature and the provided proofs against  $LRoot_{pb}$ , and it also checks whether the retrieved receipt corresponds to  $tx_i$ . In the positive case,  $C$  has a guarantee that the transaction  $tx_i$  was included in  $L$  and its execution in VM exited with a particular status, represented by a return code in the receipt.

We highlight that the previous receipt retrieval protocol assumes that  $tx_i$  is “very recent,” and is included only in the version of  $L$  that was not synchronized with  $S$  yet. When  $tx_i$  is already included in the synchronized version of  $L$ , we can put  $LRoot_{cur} = LRoot_{pb}$  in the protocol, and thus omit computation of  $\pi^{inc}$  and its verification. We also note that the receipt retrieval protocol can be integrated with the transaction submission in  $\Pi_N$  by following it.

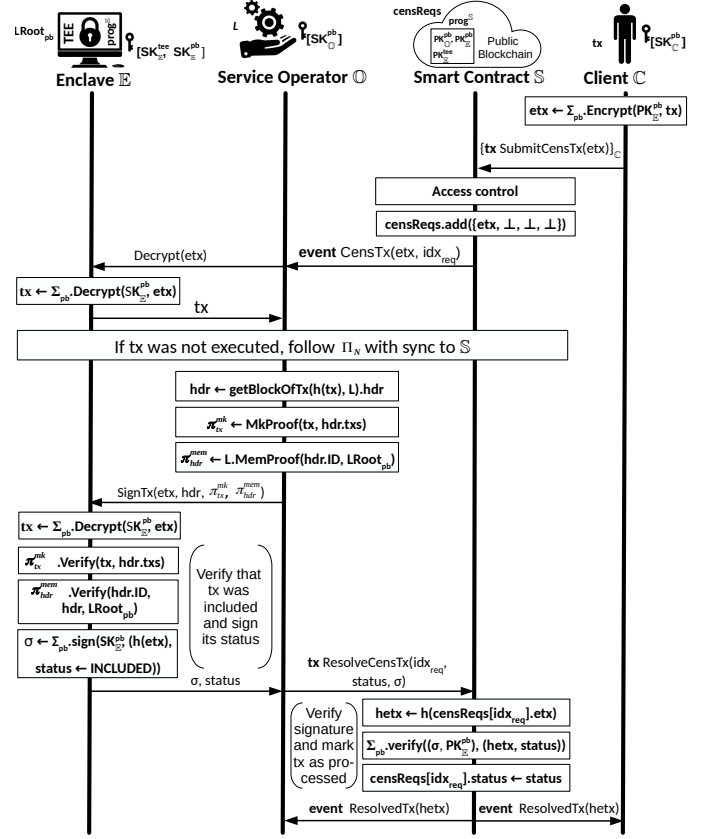


Figure 6: Protocol for resolution of a censored transaction ( $\Pi_{CT}$ ).

#### 4.4 Resolution of Censored Transactions

In the case when  $C$  suspects  $O$  of censoring a transaction  $tx$  (see Figure 6),  $C$  initiates a request for an inclusion proof of  $tx$  through  $S$ . In detail,  $C$  creates a transaction of the public blockchain platform, which calls the function  $SubmitCensTx()$  with  $tx$  encrypted by  $PK_E^{pb}$  (i.e.,  $etx$ ) as an argument and sends it to  $S$ ; hence, preserving confidentiality for public.  $S$  does the access control (see Section 6.1.2), appends  $etx$  to the list of censored requests,<sup>5</sup> and generates asynchronous event informing  $O$  about new unresolved transaction. When  $O$  receives the event, first she decrypts  $tx$  through  $E$  and then executes  $tx$  in  $E$  if it has not been executed before. If a fresh execution of  $tx$  occurred,  $O$  syncs the most recent version of  $L$  with  $S$ . Then,  $O$  sends the encrypted  $tx$  to  $E$  (i.e., function  $SignTx()$ ) together with the header and the proofs that bind  $tx$  to  $L$ , i.e., to its version  $\#(LRoot_{pb})$ . In the function  $SignTx()$  (see Algorithm 1),  $E$  decrypts  $tx$  and checks whether it is correctly parsed and whether its signature is correct. If these checks are not successful,  $E$  includes this information into a status of the response and signs it. If the checks are successful,  $E$  proceeds to the verification of provided proofs with regard to the version  $\#(LRoot_{pb})$  of  $L$  synchronized to  $S$ . Upon successful verification,  $E$  signs both the transaction's status and the hash of encrypted  $tx$ , and then returns them to  $O$ , who publishes the signature and the status through  $S$  (i.e., the function  $ResolveCensTx()$ ). When  $S$  receives the message with the status of  $tx$  signed by  $E$ , it computes the hash of  $etx$  and uses it in the

<sup>5</sup>Note that to save operational costs for allocating storage of the smart contract platform,  $S$  can store only the hash of  $etx$  instead (see Section 5.2.1).



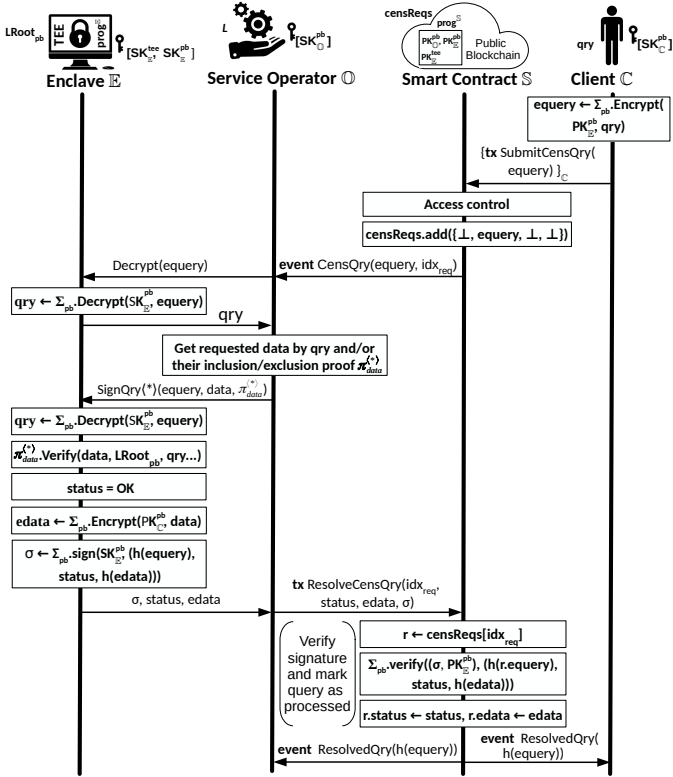


Figure 7: Protocol for resolution of a censored query ( $\Pi_{CQ}$ ).

signature verification. In the successful case,  $\mathbb{S}$  updates the status of the suspected censored transaction with the result from  $\mathbb{E}$ . Finally,  $\mathbb{S}$  notifies  $\mathbb{C}$  and  $\mathbb{O}$  about the resolution of  $tx$ .

#### 4.5 Resolution of Censored Queries

Besides censoring transactions,  $\mathbb{O}$  might also censor read queries of  $\mathbb{C}$ s. When  $\mathbb{C}$  suspects  $\mathbb{O}$  of censoring a read query  $qry$  (see Figure 7),  $\mathbb{C}$  initiates inclusion of  $qry$  through  $\mathbb{S}$ . In detail,  $\mathbb{C}$  creates a transaction of the public blockchain platform, which calls the function  $SubmitCensQry()$  (see Algorithm 2) with  $qry$  encrypted by  $PK_{\mathbb{E}}^{pb}$  (i.e.,  $equery$ ) as an argument and sends it to  $\mathbb{S}$ .  $\mathbb{S}$  does the access control (see Section 6.1.2), appends  $equery$  to the list of censored requests, and generates asynchronous event informing  $\mathbb{O}$  about new unresolved query. When  $\mathbb{O}$  receives the event, first she decrypts  $qry$  through  $\mathbb{E}$ , then fetches the data requested by  $qry$  and computes their inclusion proof(s)  $\pi_{data}^{<*>}$  in the version of  $L$  synchronized to  $\mathbb{S}$ .<sup>6</sup> Then,  $\mathbb{O}$  sends the encrypted  $qry$  to  $\mathbb{E}$  (i.e., function  $SignQry(*)()$ ) together with the fetched data and their inclusion proof  $\pi_{data}^{<*>}$ . In the function  $SignQry(*)()$ ,  $\mathbb{E}$  decrypts  $qry$  and checks whether it is correctly parsed. Upon the success,  $\mathbb{E}$  proceeds to the verification of  $\pi_{data}^{<*>}$  with regards to the passed data and the version  $\#(LRoot_{pb})$  of  $L$  synchronized with  $\mathbb{S}$ . Upon successful verification,  $\mathbb{E}$  encrypts data by  $PK_{\mathbb{C}}^{pb}$  (i.e.,  $edata$ ) and signs the triplet consisting of the transaction's status, the hash of  $eqry$ , and the hash of  $edata$ ; which are returned to  $\mathbb{O}$ . Then,  $\mathbb{O}$

<sup>6</sup>Note that if the query requests non-existing data,  $\mathbb{O}$  creates an exclusion proof instead.

calls the function  $ResolveCensQry()$  of  $\mathbb{S}$  (see Algorithm 2) with signature, status, and encrypted data contained in the arguments. When  $\mathbb{S}$  receives the message with the status of  $qry$  signed by  $\mathbb{E}$ , it computes the hashes of  $equery$  and  $edata$ , and it uses them in the signature verification. Upon successful verification,  $\mathbb{S}$  updates the status and  $edata$  of the suspected censored query with the data from  $\mathbb{E}$ . Finally,  $\mathbb{S}$  notifies  $\mathbb{C}$  and  $\mathbb{O}$  about the resolution of  $qry$ . We provide code of  $\mathbb{E}$  specific to censorship resolution and examples of handling different queries in Appendix A.1.

#### 4.6 Terminated and Failed Enclave

During the execution of  $prog^{\mathbb{E}}$ ,  $\mathbb{E}$  stores its secrets and state objects in a sealed file, which is updated and stored on the hard drive of  $\mathbb{O}$  with each new block created. Hence, if  $\mathbb{E}$  terminates due a temporary reason, such as a power outage or intentional command by  $\mathbb{O}$ , it can be initialized again by  $\mathbb{O}$  who provides  $\mathbb{E}$  with the sealed file; this file is used to recover its protected state objects.

However, if  $\mathbb{E}$  experiences a permanent hardware failure of TEE, the sealed file cannot be decrypted on other TEE platforms. Therefore, we propose a simple mechanism that deals with this situation under the assumption that  $\mathbb{O}$  is the only allowed entity that can replace the platform of  $\mathbb{E}$ . In detail,  $\mathbb{O}$  first snapshots the header  $hdr_{sync}$  of the last block that was synchronized with  $\mathbb{S}$  as well as all blocks  $blks_{unsync}$  of  $L$  that were not synchronized with  $\mathbb{S}$ . Then,  $\mathbb{O}$  restores  $L$  and her internal state objects into the version  $\#(LRoot_{pb})$ . After the restoration of  $L$ ,  $\mathbb{O}$  calls the function  $ReInit()$  of  $\mathbb{E}$  (see Algorithm 3) with  $hdr_{sync}$ ,  $blks_{unsync}$ , and  $LRoot_{pb}$  as the arguments. In this function,  $\mathbb{E}$  first generates its public/private key-pair  $SK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}$ , and then stores the passed header as  $hdr_{last}$  and copies the passed root hash into  $LRoot_{cur}$  and  $LRoot_{pb}$ . Then,  $\mathbb{E}$  iterates over all passed unprocessed blocks and their transactions  $txs$ , which are executed within VM of  $\mathbb{E}$ . Before the processing of  $txs$  of each passed block,  $\mathbb{E}$  calls the unprotected code of  $\mathbb{O}$  to obtain the current partial state  $\partial st^{old}$  of  $L$  and incremental proof template (see Section 4.2.2) that serves for extending  $L$  within  $\mathbb{E}$ . However, these unprotected calls are always verified within  $\mathbb{E}$  and malicious  $\mathbb{O}$  cannot misuse them. In detail,  $\mathbb{E}$  verifies  $\partial st^{old}$  obtained from  $\mathbb{O}$  against the root hash of the state stored in the last header  $hdr_{last}$  of  $\mathbb{E}$ , while the incremental proof template is also verified against  $LRoot_{cur}$  in the function  $newLRoot()$  of  $\mathbb{E}$ .

Next,  $\mathbb{E}$  processes  $txs$  of a block, extends  $L$ , and then it calls the unprotected code of  $\mathbb{O}$  again, but this time to process  $txs$  of

#### Algorithm 3: Reinitialization of a failed $\mathbb{E}$ (part of $prog^{\mathbb{E}}$ ).

```

function ReInit( $LRoot_{old}, prevBlks[], hdr_{last}$ ) public
( $SK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}$ )  $\leftarrow \Sigma_{pb}.Keygen();$ 
 $hdr_{last} \leftarrow hdr_{last};$ 
 $LRoot_{cur} \leftarrow LRoot_{old}, LRoot_{pb} \leftarrow LRoot_{old};$ 
for  $\{b : prevBlks\}$  do
   $\pi_{next}^{inc}, LRoot_{tmp} \leftarrow prog^{\mathbb{O}}.nextIncProof();$ 
   $\partial st^{old} \leftarrow prog^{\mathbb{O}}.getPartialState(b.txs);$ 
  assert  $\partial st^{old}.root = hdr_{last}.stRoot;$ 
   $\dots \leftarrow processTxs(b.txs, \partial st^{old}, \pi_{next}^{inc}, LRoot_{tmp});$ 
   $LRoot_{ret} \leftarrow prog^{\mathbb{O}}.runVM(b.txs);$   $\triangleright$  Run VM at  $\mathbb{O}$ .
  assert  $LRoot_{cur} = LRoot_{ret};$   $\triangleright \mathbb{E}$  and  $\mathbb{O}$  are at the same point.
 $\sigma \leftarrow \Sigma_{pb}.sign(SK_{\mathbb{E}}^{pb}, (LRoot_{pb}, LRoot_{cur}));$ 
Output( $LRoot_{pb}, LRoot_{cur}, \sigma, PK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{pb}$ );

```

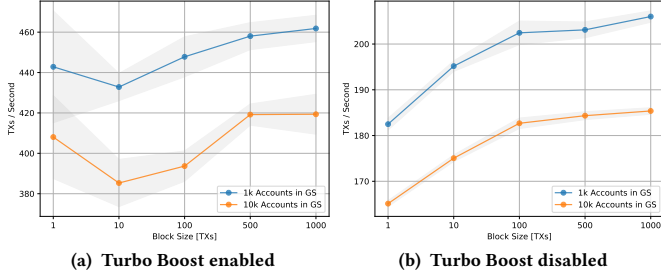


Figure 8: Performance of Aquareum for native payments.

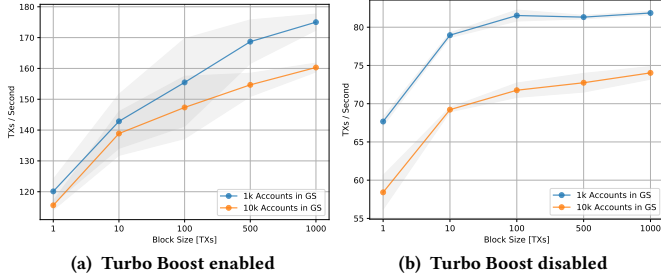


Figure 9: Performance of Aquareum for ERC20 smart contract calls.

the current block by  $\odot$ , and thus getting the same version and state of  $L$  in both  $\mathbb{E}$  and  $\odot$ . Note that any adversarial effect of this unprotected call is eliminated by the checks made after the former two unprotected calls. When all passed blocks are processed,  $\mathbb{E}$  signs the version transition pair  $\langle LRoot_{pb}, LRoot_{cur} \rangle$  and returns it to  $\odot$ , together with the new public keys of  $\mathbb{E}$ .  $\odot$  creates a blockchain transaction that calls the function  $ReplaceEnc()$  of  $\mathbb{S}$  with data from  $\mathbb{E}$  passed in the arguments. In  $ReplaceEnc()$ ,  $\mathbb{S}$  first verifies whether the signature of the transaction was made by  $\odot$  to avoid MiTM attacks on this functionality. Then,  $\mathbb{S}$  calls its function  $PostLRoot()$  with the signed version transition pair in the arguments. Upon the success, the current root hash of  $L$  is updated and  $\mathbb{S}$  replaces the stored  $\mathbb{E}$ 's PKs by PKs passed in parameters. Finally,  $\mathbb{E}$  informs  $\mathbb{C}$ s by an event containing new PKs of  $\mathbb{E}$ , and  $\mathbb{C}$ s perform the remote attestation of  $prog^{\mathbb{E}}$  using the new key  $PK_{tee}^{\mathbb{E}}$  and the attestation service. We refer the reader to Algorithm 4 in Appendix for the relevant pseudo-code of  $\odot$ .

## 5 IMPLEMENTATION

We have made a proof-of-concept implementation of Aquareum, where we utilized Intel SGX and C++ for instantiation of  $\mathbb{E}$ , while  $\mathbb{S}$  was built on top of Ethereum and Solidity. Although Aquareum can be integrated with various VMs running within  $\mathbb{E}$ , we selected EVM since it provides a Turing-complete execution environment and it is widely adopted in the community of decentralized applications. In detail, we utilized OpenEnclave SDK [38] and a minimalistic EVM, called eEVM [35]. However, eEVM is designed with the standard C++ map for storing the full state of  $L$ , which lacks efficient integrity-oriented operations. Moreover, eEVM assumes the unlimited size of  $\mathbb{E}$  for storing the full state, while the size of  $\mathbb{E}$  in SGX is constrained to  $\sim 100$  MB. This might work with enabled swapping but the performance of  $\mathbb{E}$  would be significantly deteriorated with a large full state. Due to these limitations, we replaced eEVM's full state handling by Merkle-Patricia Trie from Aleth [16], which we

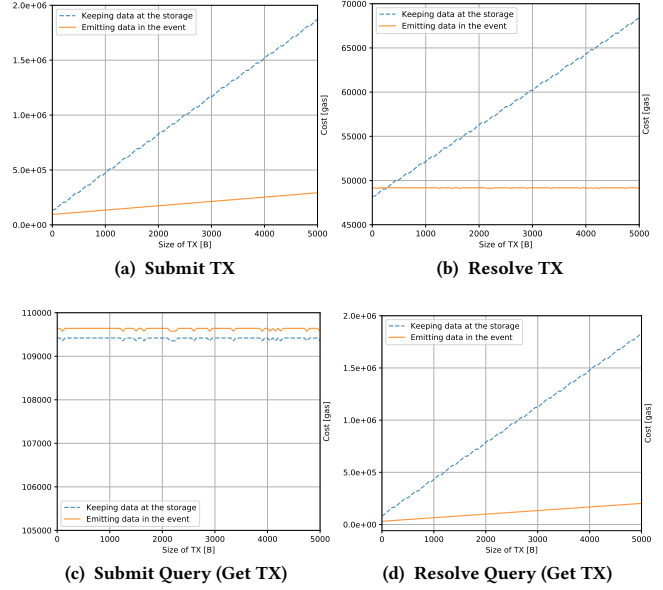


Figure 10: Costs for resolution of censored transactions and queries.

customized to support operations with the partial state.  $\odot$  and  $\mathbb{C}$  were also implemented in C++.

Our implementation enables the creation and interaction of simple accounts as well as the deployment and execution of smart contracts written in Solidity. We verified the code of  $\mathbb{S}$  by static/dynamic analysis tools Mythril [10], Slither [44], and ContractGuard [20]; none of them detected any vulnerabilities. The source code of our implementation will be made available upon publication of our work.

### 5.1 Performance Evaluation

All our experiments were performed on commodity laptop with Intel i7-10510U CPU supporting SGX v1, and they were aimed at reproducing realistic conditions – i.e., they included all operations and verifications described in Section 4, such as verification of recoverable ECDSA signatures, aggregation of transactions by Merkle tree, integrity verification of partial state, etc. We evaluated the performance of Aquareum in terms of transaction throughput per second, where we distinguished transactions with native payments (see Figure 8) and transactions with ERC20 smart contract calls (see Figure 9). All measurements were repeated 100 times, and we depict the mean and standard deviation in the graphs.

**5.1.1 A Size of the Full State.** The performance of Aquareum is dependent on a size of data that is copied from  $\odot$  to  $\mathbb{E}$  upon call of  $Exec()$ . The most significant portion of the copied data is a partial state, which depends on the height of the MPT storing the full state. Therefore, we repeated our measurements with two different full states, one containing 1k accounts and another one containing 10k accounts. In the case of native payments, the full state with 10k accounts caused a decrease of throughput by 7.8%-12.1% (with enabled TB) in contrast to the full state with 1k accounts. In the case of smart contract calls, the performance deterioration was in the range 2.8%-8.4% (with enabled TB).

**5.1.2 Block Size & Turbo Boost.** In each experiment, we varied the block size in terms of the number of transactions aggregated in the block. Initially, we performed measurements with enabled Turbo Boost (see Figure 8a and Figure 9a), where we witnessed a high throughput and its high variability. For smart contract calls (see Figure 9a), the throughput increased with the size of the block modified from 1 to 1000 by 45.7% and 38.7% for a full state with 1k and 10k accounts, respectively. However, in the case of native payments the improvement was only 4.3% and 2.8%, while the throughput was not increased monotonically with the block size.

Therefore, we experimentally disabled Turbo Boost (see Figure 8b) and observed the monotonic increase of throughput with increased block size, where the improvement achieved was 11.41% and 12.26% for a full state with 1k and 10k accounts, respectively. For completeness, we also disabled Turbo Boost in the case of smart contract calls (see Figure 9b), where the performance improvement was 20.9% and 26.7% for both full states under consideration.

## 5.2 Analysis of Costs

Besides the operational cost resulting from running the centralized infrastructure, Aquareum imposes costs for interaction with the public blockchain with  $\mathbb{S}$  deployed. The deployment cost of  $\mathbb{S}$  is 1.51M of gas and the cost of most frequent operation – syncing  $L$  with  $\mathbb{S}$  (i.e.,  $PostLRoot()$ ) – is 33k of gas, which is only 33% higher than the cost of a standard Ethereum transaction.<sup>7</sup> For example, if  $L$  is synced with  $\mathbb{S}$  every 5 minutes,  $\mathbb{O}$ 's monthly expenses for this operation would be 285M of gas, while in the case of syncing every minute, monthly expenses would be 1,425M of gas.<sup>8</sup>

**5.2.1 Censorship Resolution.** Our mechanism for censorship resolution imposes costs on  $\mathbb{C}$ s submitting requests as well as for  $\mathbb{O}$  resolving these requests. The cost of submitting a censored request is mainly dependent on the size of the request/response and whether  $\mathbb{S}$  keeps data of a request/response in the storage (i.e., an expensive option) or whether it just emits an asynchronous event with the data (i.e., a cheap option). We measured the costs of both options and the results are depicted in Figure 10. Nevertheless, for practical usage, only the option with event emitting is feasible (see solid lines in Figure 10).

Figure 10a and Figure 10b depict the resolution of a censored transaction, which is more expensive for  $\mathbb{C}$  than for  $\mathbb{O}$ , who resolves each censored transaction with constant cost 49k of gas (see Figure 10b). On the other hand, the resolution of censored queries is more expensive for  $\mathbb{O}$  since she has to deliver a response with data to  $\mathbb{S}$  (see Figure 10d), while  $\mathbb{C}$  submits only a short query, e.g., get a transaction (see Figure 10c).

## 6 SECURITY ANALYSIS AND DISCUSSION

In this section, we demonstrate resilience of Aquareum against adversarial actions that the malicious operator  $\mathcal{A}$  can perform to violate the desired properties (see Section 3.2).

**THEOREM 6.1. (Correctness)**  $\mathcal{A}$  is unable to modify the full state of  $L$  in a way that does not respect the semantics of VM deployed in  $\mathbb{E}$ .

<sup>7</sup>This cost is low since we leverage the native signature scheme of the blockchain  $\Sigma_{pb}$ .

<sup>8</sup>Representing \$305 and \$1525 as of May 2020, assuming standard gas price of 5 GWEL.

**JUSTIFICATION.** The update of the  $L$ 's state is performed exclusively in  $\mathbb{E}$ . Since  $\mathbb{E}$  contains trusted code that is publicly known and remotely attested by  $\mathbb{C}$ s,  $\mathcal{A}$  cannot tamper with this code.  $\square$

**THEOREM 6.2. (Consistency)**  $\mathcal{A}$  is unable to extend  $L$  while modifying the past records of  $L$ .

**JUSTIFICATION.** All extensions of  $L$  are performed within trusted code of  $\mathbb{E}$ , while utilizing the history tree [12] as a tamper evident data structure, which enables us to make only such incremental extensions of  $L$  that are consistent with  $L$ 's past.  $\square$

**THEOREM 6.3. (Verifiability)**  $\mathcal{A}$  is unable to unnoticeably modify or delete a transaction  $tx$  that was previously inserted to  $L$  using  $\Pi_N$ , if  $sync$  with  $\mathbb{S}$  was executed anytime afterward.

**JUSTIFICATION.** Since  $tx$  was correctly executed (Theorem 6.1) as a part of the block  $b_i$  in a trusted code of  $\mathbb{E}$ ,  $\mathbb{E}$  produced a signed version transition pair  $\{h(L_{i-1}), h(L_i)\}_{\mathbb{E}}$  of  $L$  from the version  $i - 1$  to the new version  $i$  that corresponds to  $L$  with  $b_i$  included.  $\mathcal{A}$  could either  $sync$   $L$  with  $\mathbb{S}$  immediately after  $b_i$  was appended or she could do it  $n$  versions later. In the first case,  $\mathcal{A}$  published  $\{h(L_{i-1}), h(L_i)\}_{\mathbb{E}}$  to  $\mathbb{S}$ , which updated its current version of  $L$  to  $i$  by storing  $h(L_i)$  into  $LRoot_{pb}$ . In the second case,  $n$  blocks were appended to  $L$ , obtaining its  $(i + n)$ th version.  $\mathbb{E}$  executed all transactions from versions  $(i + 1), \dots, (i + n)$  of  $L$ , while preserving correctness (Theorem 6.1) and consistency (Theorem 6.2). Then  $\mathbb{E}$  generated a version transition pair  $\{h(L_{i-1}), h(L_{i+n})\}_{\mathbb{E}}$  and  $\mathcal{A}$  posted it to  $\mathbb{S}$ , where the current version of  $L$  was updated to  $i + n$  by storing  $h(L_{i+n})$  into  $LRoot_{pb}$ . When any  $\mathbb{C}$  requests  $tx$  and its proofs from  $\mathcal{A}$  with regard to publicly visible  $LRoot_{pb}$ , she might obtain a modified  $tx'$  with a valid membership proof  $\pi_{hdr_i}^{mem}$  of the block  $b_i$  but an invalid Merkle proof  $\pi_{tx'}^{mk}$ , which cannot be forged.  $\square$

In the case of  $tx$  deletion,  $\mathcal{A}$  provides  $\mathbb{C}$  with the tampered full block  $b'_i$  (maliciously excluding  $tx$ ) whose membership proof  $\pi_{hdr_i}^{mem}$  is invalid – it cannot be forged.  $\square$

**THEOREM 6.4. (Non-Equivocation)** Assuming  $L$  synced with  $\mathbb{S}$ :  $\mathcal{A}$  is unable to provide two distinct  $\mathbb{C}$ s with two distinct valid views on  $L$ .

**JUSTIFICATION.** Since  $L$  is regularly synced with publicly visible  $\mathbb{S}$ , and  $\mathbb{S}$  stores only a single current version of  $L$  (i.e.,  $LRoot_{pb}$ ), all  $\mathbb{C}$ s share the same view on  $L$ .  $\square$

**THEOREM 6.5. (Censorship Evidence)**  $\mathcal{A}$  is unable to censor any request (transaction or query) from  $\mathbb{C}$  while staying unnoticeable.

**JUSTIFICATION.** If  $\mathbb{C}$ 's request is censored,  $\mathbb{C}$  asks for a resolution of the request through public  $\mathbb{S}$ .  $\mathcal{A}$  observing the request might either ignore it and leave the proof of censoring at  $\mathbb{S}$  or she might submit the request to  $\mathbb{E}$  and obtain an enclave signed proof witnessing that a request was processed – this proof is submitted to  $\mathbb{S}$ , whereby publicly resolving the request.  $\square$

### 6.1 Other Properties and Implications

**6.1.1 Privacy VS Performance.** Aquareum provides privacy of data submitted to  $\mathbb{S}$  during the censorship resolution since the requests and responses are encrypted. However, Aquareum does not provide privacy against  $\mathbb{O}$  who has the read access to  $L$ . Although

Aquareum could be designed with the support of full privacy, a disadvantage of such an approach would be the performance drop caused by the decryption of requested data from  $L$  upon every  $C$ 's read query, requiring a call of  $E$ . In contrast, with partial-privacy,  $O$  is able to respond queries of  $C$ s without touching  $E$ .

**6.1.2 Access Control at  $S$ .**  $C$ s interact with  $S$  only through functions for submission of censored requests. Nevertheless, access to these functions must be regulated through an access control mechanism in order to avoid exhaustion (i.e., DoS) of this functionality by external entities. This can be performed with a simple access control requiring  $C$ s to provide access tickets when calling the functions of  $S$ . An access ticket could be provisioned by  $C$  upon registration at  $O$ , and it could contain  $PK_C^{pb}$  with a time expiration of the subscription, signed by  $E$ . Whenever  $C$  initiates a censored request, verification of an access ticket would be made by  $S$ , due to which DoS of this functionality would not be possible.

**6.1.3 Security of TEE.** Aquareum assumes that its TEE platform is secure. However, recent research showed that this might not be the case in practical implementations of TEE, such as SGX that was vulnerable to memory corruption attacks [4] as well as side channel attacks [5, 48]. A number of software-based defense and mitigation techniques have been proposed [5, 7, 19, 42, 43] and some vulnerabilities were patched by Intel at the hardware level [25]. Nevertheless, we note that Aquareum is TEE-agnostic thus can be integrated with other TEEs such as ARM TrustZone or RISC-V architectures (using Keystone-enclave [15] or Sanctum [11]).

**6.1.4 Time to Finality.** Many blockchain platforms suffer from accidental forks, which temporarily create parallel inconsistent blockchain views. To mitigate this phenomenon, it is recommended to wait a certain number of block confirmations after a given block is created, considering it irreversible. This waiting time (a.k.a., time to finality) influences the non-equivocation property of Aquareum, and Aquareum inherits it from the underlying blockchain platform. Most blockchains have a long time to finality, e.g., ~3mins in Bitcoin [37], ~3mins in Ethereum [49], ~2mins in Cardano [26]. However, some blockchains have a short time to finality, e.g., HoneyBadgerBFT [36], Algorand [18], and StrongChain [45]. The selection of the underlying blockchain platform (or the protocol of the consensus layer [24]) is dependent on the requirements of the particular use case that Aquareum is applied for.

## 7 RELATED WORK

Due to their importance and potential applications, centralized ledgers, under different names (like logs, notaries, timestamp services, etc.), were extensively investigated in the literature.

**Append-Only Designs.** The first line of research is around authenticated append-only data structures. Haber and Stornetta [22] proposed a hash chain associated with transactions, proving their order. Subsequently, their work was improved [3] by aggregating transactions in a Merkle tree, allowing more efficient proofs and updates. However, these constructions still require  $O(n)$  messages to prove that one version of the ledger is an extension of another. Crosby and Wallach [12] introduced append-only logs with  $O(\log n)$ -long incremental and membership proofs. Certificate

Transparency (CT) [29] deploys this data structure to create a public append-only log of digital certificates supporting efficient membership and extension proofs, but with inefficient exclusion proofs. The idea of CT's publicly verifiable logs was then extended to other applications, like revocation transparency [28], binary transparency [17], or key transparency [33]. The CT's base construction was further improved by systems combining an append-only Merkle tree with an ordered Merkle tree [27, 41] aiming to implement a variant of an authenticated append-only dictionary. Besides making all certificates visible and append-only, these constructions use a constructed key:value mapping to prove e.g., that a certificate is revoked, or that a given domain has a certain list of certificates. These systems provide more powerful properties than CT, but unfortunately, they have inefficient  $O(n)$  proofs in verifying both properties of their logs at the same time (i.e., append-only ledger with the correct key:value mapping). A construction of append-only dictionaries with succinct proofs was recently proposed [46]. Despite achieving the desired properties, this construction relies on stronger cryptographic assumptions. Moreover, the scheme has efficiency bottlenecks as proving time grows with the data and as of today, it is impractical even for low transaction throughputs. The system also requires a trusted setup which may be unacceptable for many applications (like public ledgers). Finally, schemes of this class are designed for use cases specific to key:value databases, unable to handle smart contracts as of today.

**Non-Equivocation Designs.** Although the above systems try to minimize trust in the operator of a ledger and aim at public verifiability by deploying cryptographic constructions, they require an out of band mechanism to provide non-equivocation. One family of solutions detecting equivocations are gossip protocols, where users exchange their ledger views in order to find any inconsistencies [9, 13]. A disadvantage of these solutions is that they are primarily detective, unable to effectively prevent equivocation attacks. Moreover, these solutions are usually underspecified, and we are not aware of any system of this class deployed for this use case.

Another approach for providing the non-equivocation of a ledger was proposed by introducing multiple auditing nodes [2, 27] running a consensus protocol. Mitigations of this class, like the one proposed in Aquareum, include systems built on top of a blockchain platform (providing non-equivocation by design). An advantage of those solutions is that they are as strong as the underlying blockchain platform and with some latency (i.e., minutes) can prevent operator equivocations. Catena [47] proposes a system where a centralized log proves its non-equivocation by posting a sequence of integrity preserving transactions in the Bitcoin blockchain for its updates. However, it requires clients to obtain all Catena transactions and their number is linear with the number of log updates. PDFS [21] reduces this overhead (to constant) by a smart contract that validates consistency with the past by incremental update of the ledger using the history tree data structure (similarly, as in Aquareum); however, it does not guarantee the correct execution.

**Decentralized Designs with TEE.** Several systems combine TEE with blockchains, mostly with the intention to improve the lacking properties of blockchains like confidentiality or throughput bottlenecks. The most related work includes Teechain [30], a system where Bitcoin transactions can be executed off-chain

in TEE enclaves. By relying on properties provided by TEE, the scheme can support secure, efficient, and scalable Bitcoin transmitters. Another system is Ekiden [8], which offloads smart contract execution to dedicated TEE-supported parties. These parties can execute smart contract transactions efficiently and privately and since they are agnostic to the blockchain consensus protocol the transaction throughput can be scaled horizontally. A similar approach is taken by Das et al. [14] who propose FastKitten. In contrast to the previous work, the authors focus on backward compatibility, choosing Bitcoin as the blockchain platform and enhancing it with Turing-complete smart contracts (Bitcoin natively supports only simple smart contracts). In FastKitten, smart contracts are executed off-chain within TEE of the operator. The focus of FastKitten is the execution of multi-round smart contracts within the set of parties who interact with the operator. FastKitten supports native coins of the underlying blockchain due to SPV verification of coin locking transactions embedded into TEE. Custos [39] focuses on a detection of tampering with system logs and it utilizes TEE for the logger and decentralized auditors. However, auditors must regularly perform audit challenges to detect tampering, which is expensive and time consuming. In contrast, Aquareum provides instant efficient proofs of data genuineness or tampering upon request of the data.

## 8 CONCLUSION

In this paper, we proposed Aquareum, a framework for centralized ledgers, which provides verifiability, non-equivocation, and censorship evidence. To achieve these properties, we leveraged a combination of TEE and public blockchain with support for Turing-complete smart contracts. We showed that Aquareum is deployable with the current tools and is able to process over 450 transactions per second on a commodity PC, while accounting for the overhead of all verifications and updates.

## REFERENCES

- [1] Ittai Anati, Shay Gueron, Simon Johnson, and Vincent Scarlata. 2013. Innovative technology for CPU based attestation and sealing. In *Proceedings of the 2nd international workshop on hardware and architectural support for security and privacy*, Vol. 13. ACM New York, NY, USA.
- [2] David Basin, Cas Cremers, Tiffany Hyun-Jin Kim, Adrian Perrig, Ralf Sasse, and Pawel Szalachowski. 2014. ARPKI: Attack resilient public-key infrastructure. In *Proceedings of the 2014 ACM SIGSAC Conference on Computer and Communications Security*. 382–393.
- [3] Dave Bayer, Stuart Haber, and W Scott Stornetta. 1993. Improving the efficiency and reliability of digital time-stamping. In *Sequences II*. Springer, 329–334.
- [4] Andrea Biondo, Mauro Conti, Lucas Davi, Tommaso Frassetto, and Ahmad-Reza Sadeghi. 2018. The Guard’s Dilemma: Efficient Code-Reuse Attacks Against Intel {SGX}. In *27th {USENIX} Security Symposium ({USENIX} Security 18)*. 1213–1227.
- [5] Ferdinand Brasser, Srdjan Capkun, Alexandra Dmitrienko, Tommaso Frassetto, Kari Kostiainen, Urs Müller, and Ahmad-Reza Sadeghi. 2017. DR. SGX: hardening SGX enclaves against cache attacks with data location randomization. *arXiv preprint arXiv:1709.09917* (2017).
- [6] Melissa Chase, Apoorva Deshpande, Esha Ghosh, and Harjasleen Malvai. 2019. SEEMless: Secure End-to-End Encrypted Messaging with less Trust. In *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*. 1639–1656.
- [7] Sanchuan Chen, Xiaokuan Zhang, Michael K Reiter, and Yinqian Zhang. 2017. Detecting privileged side-channel attacks in shielded execution with Déjà Vu. In *Proceedings of the 2017 ACM on Asia Conference on Computer and Communications Security*. 7–18.
- [8] Raymond Cheng, Fan Zhang, Jernej Kos, Warren He, Nicholas Hynes, Noah Johnson, Ari Juels, Andrew Miller, and Dawn Song. 2018. Ekiden: A Platform for Confidentiality-Preserving, Trustworthy, and Performant Smart Contract Execution. *arXiv preprint arXiv:1804.05141* (2018).
- [9] Laurent Chuat, Pawel Szalachowski, Adrian Perrig, Ben Laurie, and Eran Messeri. 2015. Efficient gossip protocols for verifying the consistency of certificate logs. In *2015 IEEE Conference on Communications and Network Security (CNS)*. IEEE, 415–423.
- [10] ConsenSys. 2019. Mythril. (2019). <https://github.com/ConsenSys/mythril>
- [11] Victor Costan, Ilija Lebedev, and Srinivas Devadas. 2016. Sanctum: Minimal hardware extensions for strong software isolation. In *25th {USENIX} Security Symposium ({USENIX} Security 16)*. 857–874.
- [12] Scott A Crosby and Dan S Wallach. 2009. Efficient Data Structures For Tamper-Evident Logging. In *USENIX Security Symposium*. 317–334.
- [13] Rasmus Dahlberg, Tobias Pulls, Jonathan Vestin, Toke Høiland-Jørgensen, and Andreas Kassar. 2018. Aggregationbased gossip for certificate transparency. *CoRR abs/1806.08817, August* (2018).
- [14] Poulami Das, Lisa Eckey, Tommaso Frassetto, David Gens, Kristina Hostáková, Patrick Jauernig, Sebastian Faust, and Ahmad-Reza Sadeghi. 2019. FastKitten: practical smart contracts on bitcoin. In *28th {USENIX} Security Symposium ({USENIX} Security 19)*. 801–818.
- [15] Keystone Enclave. 2019. Keystone: An Open Framework for Architecting Trusted Execution Environments. <https://keystone-enclave.github.io/>. (2019).
- [16] Ethereum. 2019. Aleth — Ethereum C++ client, tools and libraries. (2019). <https://github.com/ethereum/aleth>
- [17] Sascha Fahl, Sergej Dechand, Henning Perl, Felix Fischer, Jaromir Smrcek, and Matthew Smith. 2014. Hey, nsa: Stay away from my market! future proofing app markets against powerful attackers. In *proceedings of the 2014 ACM SIGSAC conference on computer and communications security*. 1143–1155.
- [18] Yossi Gilad, Rotem Hemo, Silvio Micali, Georgios Vlachos, and Nickolai Zeldovich. 2017. Algorand: Scaling byzantine agreements for cryptocurrencies. In *SOSP*.
- [19] Daniel Gruss, Julian Lettner, Felix Schuster, Olya Ohrimenko, Istvan Haller, and Manuel Costa. 2017. Strong and efficient cache side-channel protection using hardware transactional memory. In *26th {USENIX} Security Symposium ({USENIX} Security 17)*. 217–233.
- [20] GuardStrike. 2019. ContractGuard. (2019). <https://contract.guardstrike.com/>
- [21] Juan Guarnizo and Pawel Szalachowski. 2019. PDFS: practical data feed service for smart contracts. In *European Symposium on Research in Computer Security*. Springer, 767–789.
- [22] Stuart Haber and W Scott Stornetta. 1990. How to time-stamp a digital document. In *Conference on the Theory and Application of Cryptography*. Springer, 437–455.
- [23] Matthew Hoekstra, Reshma Lal, Pradeep Pappachan, Vinay Phegade, and Juan Del Cuvillo. 2013. Using innovative instructions to create trustworthy software solutions. *HASP@ ISCA 11* (2013).
- [24] Ivan Homoliak, Sarad Venugopalan, Qingze Hum, Daniel Reijnsbergen, Richard Schumi, and Pawel Szalachowski. 2019. The Security Reference Architecture for Blockchains: Towards a Standardized Model for Studying Vulnerabilities, Threats, and Defenses. *arXiv preprint arXiv:1910.09775* (2019).
- [25] Intel. 2018. Resources and Response to Side Channel L1 Terminal Fault. (2018). <https://www.intel.com/content/www/us/en/architecture-and-technology/11tf.html>
- [26] Aggelos Kiayias, Alexander Russell, Bernardo David, and Roman Oliynkov. 2017. Ouroboros: A provably secure proof-of-stake blockchain protocol. In *Annual International Cryptology Conference*. Springer, 357–388.
- [27] Tiffany Hyun-Jin Kim, Lin-Shung Huang, Adrian Perrig, Collin Jackson, and Virgil Gligor. 2013. Accountable key infrastructure (AKI) a proposal for a public-key validation infrastructure. In *Proceedings of the 22nd international conference on World Wide Web*. 679–690.
- [28] Ben Laurie and Emilia Kasper. 2012. Revocation transparency. *Google Research, September* (2012), 33.
- [29] Ben Laurie, Adam Langley, and Emilia Kasper. 2013. *RFC 6962 – Certificate Transparency*. RFC 6962. RFC Editor. <https://www.rfc-editor.org/info/rfc6962>
- [30] Joshua Lind, Ittay Eyal, Florian Kelbert, Oded Naor, Peter Pietzuch, and Emin Gün Sirer. 2017. Teechain: Scalable blockchain payments using trusted execution environments. *arXiv preprint arXiv:1707.05454* (2017).
- [31] David Mazieres and Dennis Shasha. 2002. Building secure file systems out of Byzantine storage. In *Proceedings of the twenty-first annual symposium on Principles of distributed computing*. 108–117.
- [32] Frank McKeen, Ilya Alexandrovich, Alex Berenzon, Carlos V Rozas, Hisham Shafi, Vedvyas Shanbhogue, and Uday R Savagaonkar. 2013. Innovative instructions and software model for isolated execution. *Hasp@isca 10*, 1 (2013).
- [33] Marcela S Melara, Aaron Blankstein, Joseph Bonneau, Edward W Felten, and Michael J Freedman. 2015. {CONIKS}: Bringing Key Transparency to End Users. In *24th {USENIX} Security Symposium ({USENIX} Security 15)*. 383–398.
- [34] Ralph C Merkle. 1989. A certified digital signature. In *Conference on the Theory and Application of Cryptology*. Springer, 218–238.
- [35] Microsoft. 2020. Enclave EVM. (2020). <https://github.com/microsoft/eEVM>
- [36] Andrew Miller, Yu Xia, Kyle Croman, Elaine Shi, and Dawn Song. 2016. The honey badger of BFT protocols. In *ACM CCS*.
- [37] Satoshi Nakamoto. 2008. Bitcoin: A peer-to-peer electronic cash system. (2008).

- [38] Open Enclave SDK Contributors. 2020. Open Enclave SDK. (2020). <https://openenclave.io/sdk/>
- [39] Riccardo Paccagnella, Pubali Datta, Wajih Ul Hassan, Adam Bates, Christopher W Fletcher, Andrew Miller, and Dave Tian. 2020. Custos: Practical tamper-evident auditing of operating systems using trusted execution. In *Proc. of the Symposium on Network and Distributed System Security (NDSS)*.
- [40] James Ray. 2019. Modified Merkle Patricia Trie Specification. <https://github.com/ethereum/wiki/wiki/Patricia-Tree>. (2019).
- [41] Mark Dermot Ryan. 2014. Enhanced Certificate Transparency and End-to-End Encrypted Mail.. In *NDSS*. 1–14.
- [42] Jaebaek Seo, Byoungyoung Lee, Seong Min Kim, Ming-Wei Shih, Insik Shin, Dongsu Han, and Taesoo Kim. 2017. SGX-Shield: Enabling Address Space Layout Randomization for SGX Programs.. In *NDSS*.
- [43] Ming-Wei Shih, Sangho Lee, Taesoo Kim, and Marcus Peinado. 2017. T-SGX: Eradicating Controlled-Channel Attacks Against Enclave Programs.. In *NDSS*.
- [44] Slither Team. 2019. Slither. (2019). <https://github.com/crytic/slither>
- [45] Pawel Szalachowski, Daniël Reijbergen, Ivan Homoliak, and Siwei Sun. 2019. StrongChain: Transparent and Collaborative Proof-of-Work Consensus. In *USENIX*. 819–836.
- [46] Alin Tomescu, Vivek Bhupatiraju, Dimitrios Papadopoulos, Charalampos Papananthou, Nikos Triandopoulos, and Srinivas Devadas. 2019. Transparency logs via append-only authenticated dictionaries. In *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*. 1299–1316.
- [47] Alin Tomescu and Srinivas Devadas. 2017. Catena: Efficient non-equivocation via bitcoin. In *2017 IEEE Symposium on Security and Privacy (SP)*. IEEE, 393–409.
- [48] Jo Van Bulck, Marina Minkin, Ofir Weisse, Daniel Genkin, Baris Kasikci, Frank Piessens, Mark Silberstein, Thomas F Wenisch, Yuval Yarom, and Raoul Strackx. 2018. Foreshadow: Extracting the keys to the intel {SGX} kingdom with transient out-of-order execution. In *27th {USENIX} Security Symposium ({USENIX} Security 18)*, 991–1008.
- [49] Gavin Wood et al. 2014. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum project yellow paper* 151 (2014), 1–32.

## A APPENDIX

### A.1 Examples of Censored Queries

While in Section 4.5 and Figure 7 we omit the details about the data that a query might fetch, here we describe two examples.

**Get Transaction.** In the first example, a query fetches the transaction  $tx$  identified by  $id_{tx}$  that is part of the block identified by  $id_{blk}$ .<sup>9</sup> Upon notification from  $\mathbb{S}$  about unresolved request,  $\mathbb{O}$  fetches the full block with ID equal to  $id_{blk}$ ,<sup>10</sup> computes its membership proof  $\pi_{hdr}^{mem}$  in the version  $\#(LRoot_{pb})$  of  $L$ , and calls the function  $SignQryTx()$  of  $\mathbb{E}$  (see Algorithm 6) with these data in the arguments.  $\mathbb{E}$  verifies  $\pi_{hdr}^{mem}$  and search for  $tx$  with  $id_{tx}$  in the passed block. If  $tx$  is found,  $\mathbb{E}$  signs encrypted  $tx$  and the positive status of the query. On the other hand, if  $tx$  is not found in the block,  $\mathbb{E}$  signs the negative query status and empty data. The signature, the status, and encrypted  $tx$  are passed to  $\mathbb{S}$ , where the censorship of query is finished.

**Get Account State.** In the second example, a query fetches an account state  $as$  identified by  $id_{as}$  from the most recent version  $\#(LRoot_{cur})$  of  $L$ . When  $\mathbb{O}$  is notified by  $\mathbb{S}$  about an unresolved request,  $\mathbb{O}$  retrieves  $as$  from MPT trie storing the full global state of  $L$ , computes its MPT proof  $\pi_{as}^{mpt}$ ,<sup>11</sup> and calls the function  $SignQryAS()$  of  $\mathbb{E}$  (see Algorithm 6) with these data in the arguments.  $\mathbb{E}$  verifies  $\pi_{as}^{mpt}$  with regards to  $\#(LRoot_{cur})$ , and if it is a positive MPT proof,  $\mathbb{E}$  signs the encrypted  $as$  and a positive status of the query. In contrary, if  $\pi_{as}^{mpt}$  is a negative MPT proof,  $\mathbb{E}$  signs the negative query

<sup>9</sup>To verify whether the block with  $id_{blk}$  exists, we check  $id_{blk} \leq \#(LRoot_{pb})$ .

<sup>10</sup>Note that a full block is required to pass into  $\mathbb{E}$  since Merkle tree (aggregating transactions) does not support exclusion proofs, and thus all transactions of the block need to be compared.

<sup>11</sup>If  $as$  is not found,  $\pi_{as}^{mpt}$  serves as a negative proof of  $as$ .

---

### Algorithm 4: The program $prog^{\mathbb{O}}$ of service operator $\mathbb{O}$

---

▷ VARIABLES AND FUNCTIONS OF  $\mathbb{O}$ :  
 $PK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{pb}$ : public keys of enclave  $\mathbb{E}$  (under  $\Sigma_{tee}$  &  $\Sigma_{pb}$ ),  
 $PK_{\mathbb{O}}, SK_{\mathbb{O}}$ : keypair of operator  $\mathbb{O}$  (under  $\Sigma_{pb}$ ),  
 $prog^{\mathbb{E}}, prog^{\mathbb{S}}$ : program of enclave/smart contract,  
 $txs_u$ : cache of unprocessed TXs,  
 $blks_p^{\#}$ : counter of processed blocks, not synced with PB yet,  
 $\tau_{vm}, \tau_{pb}$ : time of the last flush to enclave/PB,  
 $state_{cur} \leftarrow \perp$ : current full global state of VM,  
 $censTx_s \leftarrow []$ : cache of posted censored TXs to  $\mathbb{S}$ ,  
 $L \leftarrow []$ : data of  $L$  (not synced with PB),  
 $LRoot_{pb}$ : the last root of  $L$  flushed to PB,  
 $LRoot_{cur}$ : the current root of  $L$  (not flushed to PB),  
 $\sigma_{last}$ : a signature of the last version transition pair signed by  $\mathbb{E}$ ,

▷ DECLARATION OF TYPES AND CONSTANTS:  
**Block**  $\{hdr, txs, rcps\}$ ;  
 $FL_{vm}^{\#}, FL_{pb}^{\#}$ : # of txs/blocks for flushing to enclave/PB,  
 $FL_{vm}^{\tau}, FL_{pb}^{\tau}$ : timeout for flushing to enclave/PB,

▷ DECLARATION OF FUNCTIONS:  
**function**  $Init()$   
 $PK_{\mathbb{E}}^{tee}, PK_{\mathbb{E}}^{pb} \leftarrow prog^{\mathbb{E}}.Init();$   
 $prog^{\mathbb{S}}.Init(PK_{\mathbb{E}}^{pb}, PK_{\mathbb{E}}^{tee}, PK_{\mathbb{O}});$

**function**  $UponRecvTx(tx)$   
**assert**  $accessControl(tx)$ ;  
 $txs_u.add(tx)$ ;  
**if**  $|txs_u| = FL_{vm}^{\#} \vee now() - FL_{vm}^{\tau} \geq \tau_{vm}$  **then**  
 $\pi_{next}^{inc}, LRoot_{tmp} \leftarrow nextIncProof();$   
 $LRoot_{pb}, LRoot_{cur}, \delta st^{new}, hdr, rcps, txs_{er}, \sigma_{last} \leftarrow$   
 $prog^{\mathbb{E}}.Exec(txs_u, \delta state^{cur}, \pi_{next}^{inc}, LRoot_{tmp});$   
 $state_{cur}.update(\delta st^{new});$   
 $L.add(\mathbf{Block}(hdr, txs_u \setminus txs_{er}, rcps));$   
 $txs_u \leftarrow []$ ;  $blks_p^{\#} \leftarrow blks_p^{\#} + 1$ ;  
 ▷ Sync with  $\mathbb{S}$  on public blockchain  
**if**  $blks_p^{\#} = FL_{pb}^{\#} \vee now() - FL_{pb}^{\tau} \geq \tau_{pb}$  **then**  
 $prog^{\mathbb{S}}.PostLRoot(LRoot_{pb}, LRoot_{cur}, \sigma_{last});$   
 $prog^{\mathbb{E}}.Flush();$   
 $resolveCensTx_s();$   
 $blks_p^{\#} \leftarrow 0$ ;

**function**  $nextIncProof()$   
 $LRoot_{tmp} \leftarrow L.add(\mathbf{Block}(\perp, [], []));$   
 $\pi_{next}^{inc} \leftarrow L.IncProof(LRoot_{cur}, LRoot_{tmp});$   
 $L.deleteLastBlock();$   
**return**  $\pi_{next}^{inc}, LRoot_{tmp}$ ; ▷ It serves as an incr. proof template for  $\mathbb{E}$ .

**function**  $RestoreFailedEnc()$   
 $hdr_{sync} \leftarrow L[\#(LRoot_{pb}) - 1].hdr$ ;  
 $blks_{unsync} \leftarrow L[\#(LRoot_{pb}) : -1]$ ;  
 $L.restore(\#(LRoot_{pb}))$ ; ▷ Restore all data to the target version.  
 $LRoot_A, LRoot_B, \sigma, PK_{pb}^{\mathbb{E}}, PK_{tee}^{\mathbb{E}} \leftarrow$   
 $prog^{\mathbb{E}}.ReInit(LRoot_{pb}, blks_{unsync}, hdr_{sync});$   
**assert**  $LRoot_{cur} = LRoot_A$ ; ▷  $\mathbb{E}$  and  $\mathbb{O}$  run VM into the same point.  
 $prog^{\mathbb{S}}.ReplaceEnc(PK_{pb}^{\mathbb{E}}, PK_{tee}^{\mathbb{E}}, LRoot_A, LRoot_B, \sigma);$

---

status and the empty data. The signature, status, and encrypted  $as$  are passed to  $\mathbb{S}$ , where the censorship of the query is completed.

---

**Algorithm 5: Censorship resolution in  $\mathbb{O}$  (part of  $prog^{\mathbb{O}}$ )**

---

```
function UponPostedCensTX(etx, idx_req)
  tx ← prog⊖.Decrypt(etx);
  censTxs.add({tx, etx, idx_req});
  UponRecvTx(tx); ▷ Delay response until the current block is finished.

function UponPostedCensQry(equery, idx_req)
  qry ← parse(prog⊖.Decrypt(equery));
  if READ_TX = qry.type then
    blk ← getBlockById(qry.id_blk);
    πhdrmem ← L.MemProof(blk.hdr.ID, LRootpb);
    σ, status, edata ← prog⊖.SignQryTx(equery, blk, πhdrmem);
  else if READ_AS = qry.type then
    as ← statecur.get(qry.id_as);
    πasmpt ← L.MptProof(qry.id_as); ▷ Inclusion/exclusion proof.
    σ, status, edata ← prog⊖.SignQryAS(equery, as, πasmpt);
  prog⊖.ResolveCensQry(idx_req, status, edata, σ);

function resolveCensTxs()
  for {ct : censTxs} do
    blk ← getBlockOfTx(h(ct.tx), L);
    πhdrmem ← L.MemProof(blk.hdr.ID, LRootpb);
    πtxmk ← MkProof(ct.tx, blk.txs);
    σ, status ← prog⊖.SignTx(ct.etx, πtxmk, blk.hdr, πhdrmem);
    prog⊖.ResolveCensTx(ct.idx_req, status, σ);
  censTxs ← [];
```

---

---

**Algorithm 6: Censorship resolution in  $\mathbb{E}$  (part of  $prog^{\mathbb{E}}$ ).**

---

```
function Decrypt(edata) public
  data ← Σpb.Decrypt(SK⊖pb, edata);
  Output(data);

function SignTx(etx, πtxmk, hdr, πhdrmem) public
  ▷ Resolution of a censored write tx.
  tx ← Σpb.Decrypt(SK⊖pb, etx);
  if ERROR = parse(tx) then
    status = PARSING_ERROR;
  else if ERROR = Σpb.Verify((tx.σ, tx.PKCpb), tx) then
    status = SIGNATURE_ERROR;
  else
    ▷ Verify proofs binding TX to header and header to L.
    assert πtxmk.Verify(tx, hdr.txsRoot);
    assert πhdrmem.Verify(hdr.ID, hdr, LRootpb);
    status ← INCLUDED;
    ▷ TX was processed, so  $\mathbb{E}$  can issue a proof.
  σ ← Σpb.sign(SK⊖pb, (h(etx), status));
  Output(σ, status);

function SignQryTx(equery, blk, πhdrmem) public
  ▷ Resolution of a censored read tx query.
  ... , idtx, idblk, PKCpb ← parse(Decrypt(equery));
  if idblk > #(LRootpb) then
    status ← BLK_NOT_FOUND, edata ← ⊥;
  else
    assert πhdrmem.Verify(blk.hdr.ID, blk.hdr, LRootpb);
    assert VerifyBlock(blk); ▷ Full check of block consistency.
    tx ← findTx(idtx, blk.txs);
    if ⊥ = tx then
      status ← TX_NOT_FOUND, edata ← ⊥;
    else
      status ← OK, edata ← Σpb.Encrypt(PKCpb, tx);
  σ ← Σpb.sign(SK⊖pb, (h(equery), status, edata));
  Output(σ, status, edata);

function SignQryAS(equery, as, πasmpt) public
  ▷ Resolution of a censored read account state query.
  ... , idas, PKCpb ← parse(Decrypt(equery));
  if ⊥ = as then
    assert πasmpt.VerifyNeg(idas, LRootcur);
    status ← NOT_FOUND, edata ← ⊥;
  else
    assert πasmpt.Verify(idas, LRootcur);
    status ← OK, edata ← Σpb.Encrypt(PKCpb, as);
  σ ← Σpb.sign(SK⊖pb, (h(equery), status, h(edata)));
  Output(σ, status, edata);
```

---