

Efficient Concurrent Execution of Smart Contracts in Blockchains using Object-based Transactional Memory*

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Abstract. Several popular blockchains such as Ethereum execute *complex transactions* through user-defined scripts. A block of the chain typically consists of multiple *smart contract transactions (SCTs)*. To append a block into the blockchain, a miner executes these SCTs. On receiving this block, other nodes act as *validators*, who re-execute these SCTs as part of the consensus protocol to validate the block. In Ethereum and other blockchains that support cryptocurrencies, a miner gets an incentive every time such a valid block is successfully added to the blockchain. When executing SCTs sequentially, miners and validators fail to harness the power of multiprocessing offered by the prevalence of multi-core processors, thus degrading throughput. By leveraging multiple threads to execute SCTs, we can achieve better efficiency and higher throughput. Recently, *Read-Write Software Transactional Memory Systems (RWSTMs)* were used for concurrent execution of SCTs. It is known that *Object-based STMs (OSTMs)*, using higher-level objects (such as hash-tables or lists), achieve better throughput as compared to RWSTMs. Even greater concurrency can be obtained using *Multi-Version OSTMs (MVOSTMs)*, which maintain multiple versions for each shared data-item as opposed to *Single-Version OSTMs (SVOSTMs)*.

This paper proposes an efficient framework to execute SCTs concurrently based on object semantics, using *optimistic SVOSTMs* and *MVOSTMs*. In our framework, a multi-threaded miner constructs a *Block Graph (BG)*, capturing the *object-conflicts* relations between SCTs, and stores it in the block. Later, validators re-execute the same SCTs concurrently and deterministically relying on this BG.

A malicious miner can modify the BG to harm the blockchain, e.g., to cause *double spending*. To identify malicious miners, we propose *Smart Multi-threaded Validator (SMV)*. Experimental analysis shows that proposed multi-threaded miner and validator achieve significant performance gains over state-of-the-art SCT execution framework.

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1 Introduction

Blockchains like Bitcoin [18] and Ethereum [3] have become very popular. Due to their usefulness, they are now considered for automating and securely storing user records such as land sale documents, vehicle, and insurance records. *Clients*, external users of the system, send requests to nodes to execute on the blockchain, as *smart contracts transactions (SCTs)*. An SCT is similar to the methods of a class in an object-oriented language, which encode business logic relating to the contract [5,9].

Blocks are added to the blockchain by *block-creator* nodes also known as *miners*. A miner m packs some number of SCTs received from various (possibly different) clients, to form a block B . Then, m executes the SCTs of the block sequentially to obtain the final state of the blockchain, which it stores in the block. To maintain the chain structure, m adds the hash of the previous block to the current block B and proposes this new block to be added to the blockchain.

On receiving the block B , every other node acts as a *validator*. The validators execute a global consensus protocol to decide the order of B in the blockchain. As a part of the consensus protocol, validators validate the contents of B . They re-execute all the SCTs of B sequentially to obtain the final state of the blockchain, assuming that B will be added to the blockchain. If the computed final state matches the one stored in B by the miner m then B is accepted by the validators. In this case, the miner m gets an incentive for adding B to the blockchain (in Ethereum and other cryptocurrency-based blockchains). Otherwise, B is rejected, and m does not get any reward. Ethereum follows order-execute model [6], as do several other blockchains such as Bitcoin [18], EOS [2].

Related Work: Dickerson et al. [9] observed that both miner and validators can execute SCTs concurrently and harness the power of multi-core processors. They observed another interesting advantage of concurrent execution of SCTs in Ethereum, where only the miner receives an incentive for adding a valid block while all the validators execute the SCTs in the block. Given a choice, it is natural for a validator to pick a block that supports concurrent execution and hence obtain higher throughput.

Concurrent execution of SCTs poses challenge. Consider a miner m that executes the SCTs in a block concurrently. Later, a validator v may re-execute same SCTs concurrently, in an order that may yield a different final state than given by m in B . In this case, v incorrectly rejects the valid block B proposed by m . We denote this as *False Block Rejection (FBR)*, noting that FBR may negate the benefits of concurrent execution.

Dickerson et al. [9] proposed a multi-threaded miner algorithm that is based on a *pessimistic Software Transactional Memory (STM)* and uses locks for synchronization between threads executing SCTs. To avoid FBR, the miner iden-

tifies the *dependencies* between SCTs in the block while executing them by multiple threads. Two SCTs are *dependent* if they are *conflicting*, i.e., both of them access the same data-item and at least one of them is a write. These dependencies among SCTs are recorded in the block in form of a *Block Graph (BG)*. Two SCTs that have a path in the BG are dependent on each other and cannot be executed concurrently. Later, a validator v relies on the BG to identify the dependencies among the SCTs, and concurrently execute SCTs only if there is no path between them in the BG. In the course of the execution by v , the size of BG dynamically decreases and the dependencies change. Dickerson et al. [9] use a *fork-join* approach to execute the SCTs, where a master thread allocates SCTs without dependencies to different slave threads to execute.

Anjana et al. [7] used an *optimistic* Read-Write STM (RWSTM), which identifies the conflicts between SCTs using timestamps. Those are used by miner threads to build the BG. A validator processes a block using BG in a completely decentralized manner using multiple threads, unlike the centralized fork-join approach of [9]. Each validator thread identifies an independent SCT and executes it concurrently with other threads. They showed that the decentralized approach yields significant performances gain over fork-join [9].

Saraph and Herlihy [21] used a *speculative bin* approach to execute SCTs of Ethereum in parallel. A miner maintains two bins for storing SCTs: *concurrent* and *sequential*. The SCTs are sorted into these bins using read-write locks. The *concurrent bin* stores non-conflicting SCTs while the *sequential bin* stores the remaining SCTs. If an SCT T_i requests a lock held by an another SCT T_j then T_i is rolled back and placed in the sequential bin. Otherwise, T_i is placed in the concurrent bin. To save the cost of rollback and retries of SCTs, they have used *static conflict prediction* which identifies conflicting SCTs before executing them speculatively. The multi-threaded validator in this approach executes all the SCTs of the concurrent bin concurrently and then executes the SCTs of the sequential bin sequentially. We call this the *Static Bin* approach. Zhang and Zhang [24] used *multi-version timestamp order (MVTO)* for the concurrent execution of SCTs, in a pessimistic manner.

Exploiting Object-Based Semantics: The STM-based solution of Anjana et al. [7] and others [24], rely on *read-write conflicts (rwconflicts)* for synchronization. In contrast, *object-based STMs (OSTMs)* track higher-level, more advanced conflicts between operations like insert, delete, lookup on a hash-table, enqueue/dequeue on queues, push/pop on the stack [12,13,20]. It has been shown in literature that OSTMs provide greater concurrency than RWSTMs (see Fig. 5 in Appendix A). This observation is important since Solidity [5], the language used for writing SCTs for Ethereum, extensively uses a hash-table structure called *mapping*. This indicates that a hash-table based OSTM is a natural candidate for concurrent execution of these SCTs.¹

The lock-based solution proposed by Dickerson et al. [9] used abstract locks on hash-table keys, exploiting the object-based semantics with locks. In this

¹ For clarity, we denote smart contract transactions as SCTs and an STM transaction as a transaction in the paper.

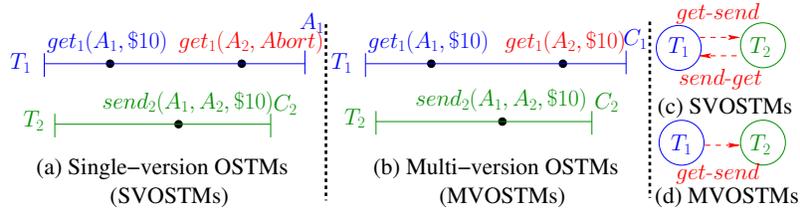


Fig. 1: (a) demonstrates two transactions T_1 and T_2 . Between two $get_balance()$ (or $get()$) of T_1 on account A_1 and A_2 (initially both accounts maintain \$10 in each), T_2 sends money from account A_1 to A_2 . Thus, T_1 gets older balance for A_1 while newer balance of A_2 . Hence, it cannot be serialized [19] (or opaque [10]). The corresponding conflict-graph has a cycle as shown in (c). To ensure the correctness, SVOSTMs abort T_1 . (b) shows the execution using MVOSTM under the same scenario as (a). By maintaining multiple versions, MVOSTM allows transaction T_1 to get the older balance for both accounts A_1 and A_2 . Hence, for this execution the equivalent serial schedule is T_1T_2 as shown in (d).

paper, we want to exploit the object semantics of hash-tables using optimistic STMs to improve the performance obtained.

To capture the dependencies between the SCTs in a block, miner threads construct the BG concurrently and append it to the block. The dependencies between the transactions are given by the *object-conflicts* (*oconflicts*) (as opposed to *rwconflicts*) which ensure that the execution is correct, i.e., satisfies *conflict-opacity* [20]. It has been shown [12,13,20] that there are fewer *oconflicts* than *rwconflicts*. Since there are fewer *oconflicts*, the BG has fewer edges which in turn, allows validators to execute more SCTs concurrently. This also reduces the size of the BG leading to a smaller communication cost.

Multi-version object STMs (MVOSTMs) [16] demonstrate that by maintaining multiple versions for each shared data-item (object), even greater concurrency can be obtained as compared to traditional *single-version OSTMs (SVOSTMs)*. Fig. 1 illustrates the benefits of concurrent execution of SCTs by miner using MVOSTM over SVOSTM. Thus a BG based on MVOSTM will have fewer edges than an SVOSTM-based BG, and will further reduce the size of the BG stored in the block. These advantages motivated us to use MVOSTMs for concurrent execution of SCTs by miners.

Concurrent executions of SCTs may cause inconsistent behaviors such as *infinite loops*, *divide by zero*, *crash failures*. Some of these behaviors, such as crash failures can be mitigated when SCTs are executed in a controlled environment, for example, the *Ethereum Virtual Machine (EVM)* [3]. However, not all anomalies such as infinite loop can be prevented by the virtual machine. The inconsistent executions can be prevented by ensuring that the executions produced by the STM system are opaque [10] or one of its variants such as *co-opacity* [20]. Our MVOSTM satisfies the former condition, opacity, while our SVOSTM satisfies the latter one, co-opacity.

Handling a Malicious Miner: A drawback of some of the approaches mentioned above is that a malicious miner can make the final state of the blockchain be inconsistent. In the BG approach, the miner proposes an incorrect BG which does not include all necessary edges. With the bin-based approach, the miner could place the conflicting transactions in the concurrent bin [21]. This can result in inconsistent states in the blockchain due to *double spending*, e.g., when two concurrent transactions incorrectly transfer the same amount of money simultaneously from a source account to two different destination accounts. If a malicious miner *mm* does not add an edge between these two transactions in the BG [7] or put these two transactions in concurrent bin [21] then both SCTs can execute concurrently by validators. Similarly, if a majority of validators accept the block containing these two transactions, then the state of the blockchain becomes inconsistent. We denote this problem as *edge missing BG (EMB)* in the case of the BG approach [7] and *faulty bin (FBin)* in the case of the bin-based approach [21]. In Section 4, we show the effect of malicious miners (EMB or FBin) through experiments on the blockchain system.

To handle EMB and FBin errors, the validator must reject a block when edges are missing in the BG or when conflicting SCTs are in the concurrent bin. Execution of such a graph or concurrent bin by the validator threads can lead to an inconsistent state. To detect such an execution, the validator threads watch and identify transactions performing conflicting access on the same data-items while executing concurrently. In Section 3, we propose a *Smart Multi-threaded Validator (SMV)* which uses *counters* to detect this condition and reject the corresponding blocks.

Dickerson et al. [9] suggest a lock-based solution to handle EMB errors. The miner generates and stores the lock profile required to execute the SCTs of a block along with the BG. The validator then records a trace of the locks each of its thread would have acquired, had it been executing speculatively independent of the BG. The validator would then compare the lock profiles it generated with the one provided by the miner present in the block. If the profiles are different then the block is rejected. This check is in addition to the check of the final state generated and the state in the block. This solution is effective in handling EMB errors caused by malicious miners. However, it is lock-based and cannot be used for preventing EMB issue in optimistic approaches such as [7]. The advantage of our SMV solution is that it works well with both optimistic and lock-based approaches.

Our Contributions: This paper develops an efficient object semantics framework to execute SCTs concurrently by a miner using optimistic hash-table (both single and multi-version) OSTM. We use two methodologies to re-execute the SCTs concurrently by validators. In addition to the *fork-join approach* employed by Dickerson et al. [9], we also use a *decentralized approach* [7] in which the validator threads execute independent SCTs concurrently in a decentralized manner. To handle EMB and FBin errors, we propose a decentralized *Smart Multi-threaded Validator*. To summarize:

- We introduce an efficient object-based framework for the concurrent execution of SCTs by miners (Section 3.2). We propose a novel way to execute the SCTs efficiently using optimistic SVOSTM by miner while ensuring *co-opacity* [20]. To further increase concurrency, we propose a new way for the execution of SCTs by the miner using optimistic MVOSTM [16] while satisfying opacity [10].
- We propose the concurrent execution of SCTs by validators using BG given by miner to avoid FBR error (Section 3.3). The validator executes the SCTs using either fork-join or decentralized approaches.
- We propose a Smart Multi-threaded Validator to handle EMB and FBin errors caused by malicious miners (Section 3.4).
- Extensive simulations (Section 4) show that concurrent execution of SCTs by SVOSTM and MVOSTM miner provide an average speedup of $3.41\times$ and $3.91\times$ over serial miner, respectively. SVOSTM and MVOSTM based decentralized validator provide on average of $46.35\times$ and $48.45\times$ over serial validator, respectively.

2 System Model

As in [11,17], we consider n threads, p_1, \dots, p_n in a system that access shared data-items (or objects/keys) in a completely asynchronous fashion. We assume that none of the threads/processes will crash or fail unexpectedly.

Events: A thread invokes the transactions and the transaction calls object level (or higher-level) methods which internally invokes read/write atomic events on the shared data-items to communicate with other threads. Method invocations (or *inv*) and responses (or *rsp*) are also considered as events.

History: It is a sequence of invocations and responses of different transactional methods. We consider *sequential history* in which invocation on each transactional method follows the immediate matching response.

In this paper, we consider only *well-formed* histories in which a new transaction will not begin until the invocation of previous transaction has not been committed or aborted.

Software Transactional Memory (STM): STM [17,22] is a convenient concurrent programming interface for a programmer to access the shared memory using multiple threads. A typical STM works at lower-level (read-write) and exports following methods: (1) `STM.begin()`: begins a transaction with unique id. (2) `STM.read(k)` (or $r(k)$): reads the value of data-item k from shared memory. (3) `STM.write(k, v)` (or $w(k, v)$): writes the value of data-item k as v in its local log. (4) `STM.tryC()`: validates the transaction. If all updates made by the transaction is consistent then the updates will be reflected onto shared memory and transaction returns *commit* (or \mathcal{C}). Otherwise, transaction returns *abort* (or \mathcal{A}). Transaction T_i starts with `STM.begin()` and completes when any of its methods return abort (or \mathcal{A}) or commit (or \mathcal{C}). The `STM.read()` and `STM.tryC()` methods may return \mathcal{A} .

OSTMs export higher-level methods: (1) `STM.begin()`: begins a transaction with unique id. (2) `STM.lookup(k)` (or $l(k)$): does a lookup on data-item k from

shared memory. (3) $STM_insert(k, v)$ (or $i(k, v)$): inserts the value of data-item k as v in its local log. (4) $STM_delete(k)$ (or $d(k)$): deletes the data-item k . (5) $STM_tryC()$: validates the transaction. After successful validation, the actual effects of $STM_insert()$ and $STM_delete()$ will be visible in the shared memory and transaction returns \mathcal{C} . Otherwise, it will return \mathcal{A} . We represent $STM_lookup()$, and $STM_delete()$ as *return-value* (rv) methods because both methods return the value from hash-table. We represent $STM_insert()$, and $STM_delete()$ as *update* (upd) methods as on successful $STM_tryC()$ both methods update the shared memory. Methods $rv()$ and $STM_tryC()$ may return \mathcal{A} . For a transaction T_i , we denote all the objects accessed by its $rv_i()$ and $upd_i()$ methods as $rvSet_i$ and $updSet_i$, respectively.

Valid and Legal History: If the successful $rv_j(k, v)$ (i.e., $v \neq \mathcal{A}$) method of a transaction T_j returns the value from any of previously committed transaction T_i that has performed $upd()$ on key k with value v then such $rv_j(k, v)$ method is *valid*. If all the $rv()$ methods of history H is valid then H is valid history [20].

If the successful $rv_j(k, v)$ (i.e., $v \neq \mathcal{A}$) method of a transaction T_j returns the value from previous closest committed transaction T_i that $k \in updSet_i$ (T_i can also be T_0) and updates the k with value v then such $rv_j(k, v)$ method is *legal*. If all the $rv()$ methods of history H is legal then H is legal history [20]. A legal history is also valid history.

Two histories H and H' are *equivalent* if they have the same set of events. H and H' are *multi-version view equivalent* [23, Chap. 5] if they are valid and equivalent. H and H' are *view equivalent* [23, Chap. 3] if they are legal and equivalent. Additional definitions are in Appendix B.

3 Proposed Mechanism

This section describes our approach to the construction, data structures, and methods of concurrent BG, concurrent execution of SCTs by multi-threaded miner using optimistic object-based STMs, multi-threaded validator, and detection of a malicious miner.

3.1 The Block Graph

The multi-threaded miner executes the SCTs concurrently and stores the dependencies among them in a BG. Each committed transaction corresponding to an SCT is a vertex in the BG while edges capture the dependencies, based on the STM protocol. Multi-threaded miner uses SVOSTM and MVOSTM to execute the SCTs concurrently, using timestamps. The challenge here is to construct the BG concurrently without missing any dependencies.

SVOSTM-based miner maintains three types of edges based on oconflicts between the transactions. An edge $T_i \rightarrow T_j$ between two transaction is defined when: **(1)** $rv_i(k, v) - STM_tryC_j()$ edge : if $rv_i(k, v) <_H STM_tryC_j()$, $k \in updSet(T_j)$ and $v \neq \mathcal{A}$; **(2)** $STM_tryC_i() - rv_j(k, v)$ edge : if $STM_tryC_i() <_H rv_j(k, v)$, $k \in updSet(T_i)$ and $v \neq \mathcal{A}$; **(3)** $STM_tryC_i() - STM_tryC_j()$ edge : if $STM_tryC_i() <_H STM_tryC_j()$ and $(updSet(T_i) \cap updSet(T_j) \neq \emptyset)$.

MVOSTM-based miner maintains two types of edges based on *multi-version oconflicts* (*mvoconflicts*) [16]. **(1) return value from (rvf) edge:** if $STM_tryC_i() <_H rv_j(k, v)$, $k \in updSet(T_i)$ and $v \neq \mathcal{A}$ then there exist an *rvf edge* from T_i to T_j , i.e., $T_i \rightarrow T_j$; **(2) multi-version (mv) edge:** consider a triplet, $STM_tryC_i(), rv_m(k, v), STM_tryC_j()$ in which $(updSet(T_i) \cap updSet(T_j) \cap rvSet(T_m) \neq \emptyset)$, (T_i and T_j update the key k with value v and u respectively) and $(u, v \neq \mathcal{A})$; then there are two types of *mv edge*: (a) if $STM_tryC_i() <_H STM_tryC_j()$ then there exist a *mv edge* from T_m to T_j . (b) if $STM_tryC_j() <_H STM_tryC_i()$ then there exist a *mv edge* from T_j to T_i . We modified SVOSTM and MVOSTM to capture oconflicts and mvoconflicts in the BG.

Data Structure for the Block Graph: We use *adjacency lists* to maintain the $BG(V, E)$. V is the set of vertices (or SCTs) stored as a vertex list and E is the set of edges (conflicts between SCTs) stored as edge list. Two lock-free methods build the BG (see details in Appendix C.1): *addVertex()* adds a vertex and *addEdge()* adds an edge in BG. To execute the SCTs, validator threads use three methods of block graph library: *globalSearch()* identifies the independent vertex with indegree 0 to execute it concurrently, *remExNode()* decrements the indegree of conflicting vertices and *localSearch()* identifies the independent vertex in thread local.

3.2 Multi-threaded Miner

A miner m receives requests to execute SCTs from different clients. The miner m then forms a block with several SCTs (the precise number of SCTs depend on the blockchain), m execute these SCTs while executing the non-conflicting SCTs concurrently to obtain the final state of the blockchain. Identifying the non-conflicting SCTs statically is not straightforward because smart contracts are written in a turing-complete language [9] (e.g., Solidity [5] for Ethereum). We use optimistic STMs to execute the SCTs concurrently as in Anjana et al. [7] but adapted to object-based STMs on hash-tables to identify the conflicts.

Algorithm 1 shows how SCTs are executed by an m threaded miner. The input is an array of SCTs, *sctList* and a object-based STM, (SVOSTM or MVOSTM). We assume that both libraries support the BG methods described above. The multi-threaded miner uses a global index into the *sctList* *gIndex* which is accessed by all the threads. A thread Th_x first reads the current value of *gIndex* into a local value *curInd* and increments *gIndex* atomically (Line 2).

Having obtained the current index in *curInd*, Th_x gets the corresponding SCT, *curTrn* from *sctList*[] (Line 4). Th_x then begins a STM transaction corresponding to *curTrn* (Line 5). For every hash-table insert, delete and lookup encountered while executing the *scFun* of *curTrn*, Th_x invokes the corresponding STM methods: *STM_lookup()*, *STM_insert()*, *STM_delete()*, either on an SVOSTM or on an MVOSTM. Otherwise, it executes the step normally. If any of these steps fail, Th_x begins a new STM transaction (Line 5) and re-executes these steps.

Upon successful completion of transaction T_i , Th_x creates a vertex node for T_i in the block graph (Line 21). Then, Th_x obtains the transactions (SCTs) with

Algorithm 1 Multi-threaded Miner($sctList[]$, STM): m threads concurrently execute the SCTs from $sctList$ with STMs.

```

1: procedure Multi-threaded Miner ( $sctList[]$ , STM)
2:    $curInd = gIndex.get\&Inc()$ ; // Atomically read the index and increment it.
3:   while ( $curInd < sctList.length$ ) do // Execute until all SCTs have not been executed
4:      $curTrn = sctList[curInd]$ ; // Get the current SCT to execute
5:      $T_i = STM.begin()$ ; // Begins a new transaction. Here  $i$  is unique id
6:     for all ( $curStep \in curTrn.scFun$ ) do // scFun is a list of steps
7:       switch( $curStep$ )
8:         case lookup( $k$ ):
9:            $v \leftarrow STM.lookup(k)$ ; // Lookup data-item  $k$  from a shared memory
10:          if( $v == \mathcal{A}$ ) then goto Line 5; end if break;
11:          case insert( $k, v$ ): // Insert data-item  $k$  into  $T_i$  local memory with value  $v$ 
12:            STM.insert( $k, v$ ); break;
13:          case delete( $k$ ):
14:             $v \leftarrow STM.delete(k)$ ; // Actual deletion of data-item  $k$  happens in STM.tryC()
15:            if( $v == \mathcal{A}$ ) then goto Line 5; end if break;
16:          default: Execute the step normally // Any step apart from lookup, insert, delete
17:        endswitch
18:      end for
19:       $v \leftarrow STM.tryC()$ ; // Try to commit the transaction  $T_i$ 
20:      if( $v == \mathcal{A}$ ) then goto Line 5; end if
21:      addVertex( $i$ ); // Create vertex node for  $T_i$  with scFun
22:      BG( $i$ , STMs); // Add the conflicts of  $T_i$  to block graph
23:       $curInd = gIndex.get\&Inc()$ ; // Atomically read the index and increment it.
24:    end while
25:    build-block(); // Here the miner builds the block.
26: end procedure

```

which T_i is conflicting from the OSTM, and adds the corresponding edges to the BG (Line 22). Th_x then gets the index of the next SCT to execute (Line 23).

An important step here is how the underlying OSTMs (either SVOSTM or MVOSTM) maintain the conflicts among the transactions which is used by Th_x (see Appendix C.2). Both SVOSTM and the MVOSTM use timestamps to identify the conflicts.

Once all the SCTs of $sctList$ have been executed successfully and the BG is constructed concurrently, it is stored in the proposed block. The miner then stores the final state (FS_m) of the blockchain (which is the state of all shared data-items), resulting from the execution of SCTs of $sctList$ in the block. The miner then computes the operations related to the blockchain. For Ethereum, this would constitute the hash of the previous block. Then the multi-threaded miner proposes a block which consists of all the SCTs, BG, FS_m of all the shared data-items and hash of the previous block (Line 25). The block is then broadcast to all the other nodes in the blockchain.

Appendix D proves the following theorems:

Theorem 1. *The BG captures all the dependencies between the conflicting nodes.*

Theorem 2. *A history H_m generated by the multi-threaded miner with SVOSTM satisfies co-opacity.*

Theorem 3. *A history H_m generated by multi-threaded miner with MVOSTM satisfies opacity.*

3.3 Multi-threaded Validator

The validator re-executes the SCTs deterministically relying on the BG provided by the miner in the block. BG consists of dependency among the conflicting SCTs and restrict validator threads to execute them serially to avoid the *False Block Rejection (FBR) error* while non-conflicting SCTs execute concurrently to obtain greater throughput. The validator uses *globalSearch()*, *localSearch()*, and *remExNode()* methods of the BG library as described in Section 3.1.

After successful execution of the SCTs, validator threads compute the final state (FS_v) of the blockchain which is the state of all shared data items. If it matches the final state FS_m provided by the miner then the validator accepts the block. If a majority of the validators accept the block, then it is added to the blockchain. Detailed description appears in Appendix C.3.

Appendix D proves the following theorems:

Theorem 4. *A history H_m generated by the multi-threaded miner with SVOSTM and history H_v generated by a multi-threaded validator are view equivalent.*

Theorem 5. *A history H_m generated by the multi-threaded miner with MVOSTM and history H_v generated by a multi-threaded validator are multi-version view equivalent.*

3.4 Detection of Malicious Miners by Smart Multi-threaded Validator (SMV)

We propose a technique to handle edge missing BG (EMB) and Faulty Bin (FBin) caused by the malicious miner as explained in Section 1. A malicious miner mm can remove some edges from the BG and set the final state in the block accordingly. A multi-threaded validator executes the SCTs concurrently relying on the BG provided by the mm and results the same final state. Hence, incorrectly accepts the block. Similarly, if a majority of the validators accept the block then the state of the blockchain becomes inconsistent. For instance, a double spending can be executed.

A similar inconsistency can be caused by a mm in bin-based approach: mm can maliciously add conflicting SCTs to the concurrent bin resulting in FBin error. This may cause multi-threaded validator v to access shared data items concurrently leading to synchronization errors. To prevent this, the SMV checks to see if two concurrent threads end up accessing the same shared data item concurrently. If this situation is detected, then the miner is malicious.

To identify such situations, SMV uses *counters*, inspired by the *basic timestamp ordering (BTO)* protocol in databases [23, Chap. 4]. SMV keeps track of each global data item that can be accessed across multiple transactions by different threads. Specifically, SMV maintains two global counters for each key of hash-table (shared data item) k (a) $k.gUC$ - global update counter (b) $k.gLC$ - global lookup counter. These respectively keep track of number of **updates** and **lookups** that are concurrently performed by different threads on k . Both counters are initially 0.

When an SMV thread Th_x is executing an SCT T_i it maintains two local variables corresponding to each global data item k which is accessible only by Th_x (c) $k.lUC_i$ - local update counter (d) $k.lLC_i$ - local lookup counter. These respectively keep track of number of updates and lookups performed by Th_x on k while executing T_i . These counters are initialized to 0 before the start of T_i .

Having described the counters, we will explain the algorithm at a high level. Suppose the next step to be performed by Th_x is:

1. *lookup(k)*: Thread Th_x will check for equality of the local and global update counters, i.e., $(k.lUC_i == k.gUC)$. If they are not same then SMV will report the miner as malicious. Otherwise, (i) Th_x will atomically increment $k.gLC$. (ii) Th_x will increment $k.lLC_i$. (iii) Perform the lookup on the key k from shared memory.
2. *update(k, val)*: Here Th_x wants to update (insert/delete) k with value val . So, Th_x will check for the equality of both global, local update and lookup counters, i.e., $(k.lUC_i == k.gUC)$ and $(k.lLC_i == k.gLC)$. If they are not same then SMV will report the miner as malicious. Otherwise, (i) Th_x will atomically increment $k.gUC$. (ii) Th_x will increment $k.lUC_i$. (iii) Perform the update on the key k with value val on shared memory.

Once T_i terminates, Th_x will atomically decrements $k.gUC, k.gLC$ by the value of $k.lUC_i, k.lLC_i$, respectively. Then Th_x will reset $k.lUC_i, k.lLC_i$ to 0.

The reason for performing these steps and the correctness of the algorithm is as follows: if Th_x is performing a lookup on k then no other thread should be performing an update on k . Here, $k.gUC$ represents the number of updates to k currently executed by all the threads while $k.lUC_i$ represents the number of updates to k on behalf of T_i by Th_x . Thus the value of gUC should be same as lUC . Otherwise, some other thread is also concurrently performing the updates to k . Similarly, if Th_x is performing an update on k , then no other thread should be performing an update or lookup on k . This can be verified by checking if lLC, lUC are respectively same as gLC, gUC .

Theorem 6. *Smart Multi-threaded Validator rejects malicious blocks with BG that allow concurrent execution of dependent SCTs.*

The same SMV technique can be applied to identify the *faulty bin* error as explained in Section 1. See Appendix C.4 for detailed description along with the pseudo code of smart multi-threaded validator and Appendix D for proof of Theorem 6.

4 Experimental Evaluation

The goal of this section is to demonstrate the performance gains by proposed multi-threaded miner and validator against state-of-the-art miners and validators. To evaluate our approach, we considered Ethereum smart contracts. In Ethereum blockchain, contracts are written in Solidity [5] language and are executed on the *Ethereum Virtual Machine (EVM)* [3]. EVM does not support

multi-threading [3,9]. So, we converted the smart contracts of Ethereum as described in Solidity documentation [5] into C++ multi-threaded contracts similar to the approach of [7,9]. Then we integrated them into object-based STM framework (SVOSTM and MVOSTM) for concurrent execution of SCTs by the miner.

We chose a diverse set of smart contracts described in Solidity documentation [5] as benchmarks to analyze the performance of our proposed approach as was done in [7,9]. The selected benchmark contracts are (1) *Coin*: a financial contract, (2) *Ballot*: an electronic voting contract, (3) *Simple Auction*: an auction contract, and (4) finally, a *Mix* contract: combination of three contracts mentioned above in equal proportion in which block consists of multiple SCTs belonging to different smart contracts and seems more realistic.

We compared the proposed SVOSTM and MVOSTM miner with state-of-the-art multi-threaded: BTO [7], MVTO [7], Speculative Bin (or SpecBin) [21], Static Bin (or StaticBin) [21], and Serial miner.² We could not compare our work with Dickerson et al. [9] as their source code is not available in public domain. We converted the code of StaticBin and SpecBin [21] from Java to C++ for comparing with our algorithms.

Concurrent execution of SCTs by the validator does not use any STM protocol; however it uses the BG provided by the multi-threaded miner, which does use STM. To identify malicious miners and prevent any malicious block from being added to the blockchain, we proposed Smart Multi-threaded Validator (SMV) for SVOSTM, MVOSTM as SVOSTM SMV, MVOSTM SMV. Additionally, we proposed SMV for state-of-the-art validators as BTO SMV, MVTO SMV, SpecBin SMV, and StaticBin SMV and analysed the performance.

Experimental Setup: The experimental system consists of two sockets, each comprised of 14 cores 2.60 GHz Intel (R) Xeon (R) CPU E5-2690, and each core supports 2 hardware threads. Thus the system supports a total of 56 hardware threads. The machine runs Ubuntu 16.04.2 LTS operating system and has 32GB RAM.

To analyze the performance, we evaluated the speedup achieved by each contract on two workloads. In the first workload (W1), the number of SCTs varied from 50 to 300 while the number of threads fixed is at 50. The maximum number of SCTs in a block of Ethereum is approximately 250 [4,9], but is growing over time. In the second workload (W2), the number of threads varied from 10 to 60, while the number of SCTs is fixed at 100. The average number of SCTs in a block of Ethereum is around 100 [4]. The hash-table size and shared data-items are fixed to 30 and 500 respectively for both workloads. For accuracy, results are averaged over 26 runs in which the first run is discarded and considered as a warm-up run. The results of serial execution is treated as the baseline for evaluating the speedup. This section describes the detailed analysis for the mix contract and analysis of Coin, Ballot and Simple auction benchmark contracts are in Appendix E.

Experimental Results: Fig. 2 (a) and Fig. 2 (b) show the speedup of MVOSTM, SVOSTM, MVTO, BTO, SpecBin, and StaticBin miner over serial miner for mix

² Code is available here: <https://github.com/PDCRL/ObjSC>

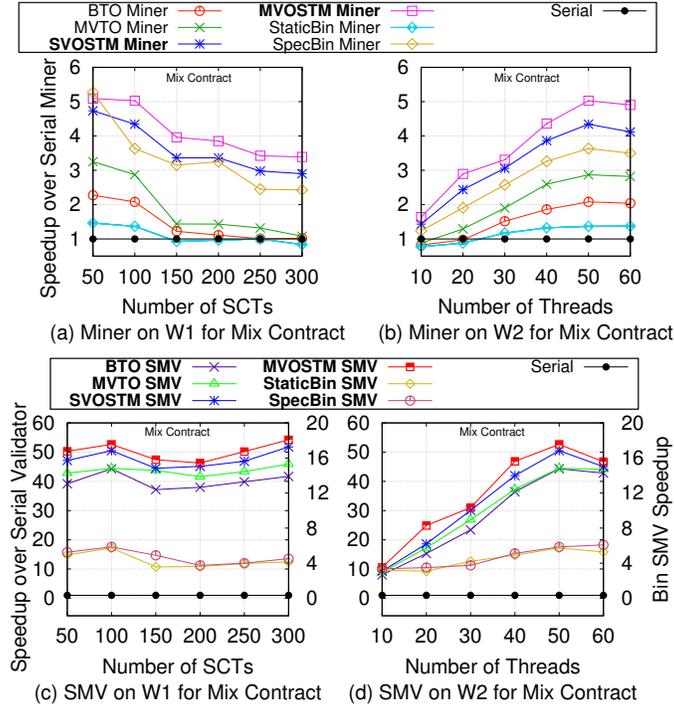


Fig. 2: Multi-threaded and SMVs Speedup over Serial Miner and Validator for Mix Contract on W1 and W2

contract on workloads W1 and W2, respectively.³ The average speedup achieved by MVOSTM, SVOSTM, MVTO, BTO, SpecBin, and StaticBin miner over serial miner is $3.91\times$, $3.41\times$, $1.98\times$, $1.5\times$, $3.02\times$, and $1.12\times$, respectively.

As shown in Fig. 2 (a), increasing the number of SCTs leads to high contention (because shared data-items are fixed to 500). So the speedup of multi-threaded miner reduces. MVOSTM and SVOSTM miners outperform SpecBin miner because MVOSTM and SVOSTM miners use optimistic object-based STMs to execute SCTs concurrently and construct the BG whereas SpecBin uses locks to execute SCTs concurrently and constructs two bins using the pessimistic approach. SpecBin miner does not release the locks until the construction of the concurrent bin, which gives less concurrency. However, for the smaller numbers of SCTs in a block, SpecBin is slightly better than MVOSTM and SVOSTM miners, which can be observed in the Fig. 2 (a) at 50 SCTs. MVOSTM and SVOSTM miners outperform MVTO and BTO miners because both of them are consider rwconflicts. It can also be observed that MVOSTM miner outperforms all other STM miners as it has fewer conflicts, which gets reflected (see Fig. 4) as the least number of dependencies in the BG as compared to other STM miners. For the multi-version (MVOSTM and MVTO) miners, we did not

³ In the figures, legend items in bold.

limit the number of versions because the number of SCTs in a block is finite. The speedup by StaticBin miner is worse than serial miner for more than 100 SCTs because it takes time for *static conflict prediction* before executing SCTs.

Fig. 2 (b) shows that speedup achieved by multi-threaded miner increases while increasing the number of threads, limited by the number of hardware threads available on the underlying experimental setup. Since, our system has 56 logical threads, the speedup decreases beyond 56 threads. MVOSTM miner outperforms all other miners with similar reasoning, as explained for Fig. 2 (a). Another observation is that when the number of threads is less, the serial miner dominates BTO and MVTO miner due to the overhead of the STM system.

The average number of dependencies in BG by all the STM miners presented in Fig. 4. It shows that BG constructed by the MVOSTM has the least number of edges for all the contracts on both workloads. However, there is no BG for bin-based approaches (both SpecBin and StaticBin). So, from the block size perspective, bin-based approaches are efficient. But the speedup of the validator obtained by the bin-based approaches is significantly lesser than STM validators.

Fig. 2 (c) and Fig. 2 (d) show the speedup of Smart Multi-threaded Validators (SMVs) over serial validator on the workloads W1 and W2, respectively. The average speedup achieved by MVOSTM, SVOSTM, MVTO, BTO, SpecBin, and StaticBin decentralized SMVs are $48.45\times$, $46.35\times$, $43.89\times$, $41.44\times$, $5.39\times$, and $4.81\times$ over serial validator, respectively.

It can be observed that decentralized MVOSTM SMV is best among all other STM validators due to fewer dependencies in the BG. Though the block size is less in bin-based approaches as compared to STM based approaches due to the absence of BG, however, STM validators outperform bin-based validators because STM validators precisely determines the concurrent SCTs based on BG. In contrast, bin-based validator gives less concurrency using a lock-based pessimistic approach.

The speedup of SMV is significantly higher than multi-threaded miner because the miner has to execute the SCTs concurrently either using STMs (including the retries of aborted transactions) and constructs the BG or prepare two bins (concurrent and sequential bin using locks in SpecBin and static analysis in StaticBin). On the other hand, the validator executes the SCTs concurrently and deterministically relying on BG (without any retries) or bins provided by miner.

A malicious miner may cause either EMB or FBin errors in a block. Fig. 3 illustrates the percentage of validators without SMV logic embedded, i.e., Non-SMV accepting a malicious block on workloads W1 and W2, respectively. Here, we considered 50 validators and ran the experiments for the mix contract. The Fig. 3 shows that less than 50% of validators (except bin-based NonSMV) accept a malicious block. However, SpecBin and StaticBin NonSMVs show more than 50% acceptance of malicious blocks. Though, it is to be noted that the acceptance of even a single malicious block result in the blockchain going into inconsistent state.

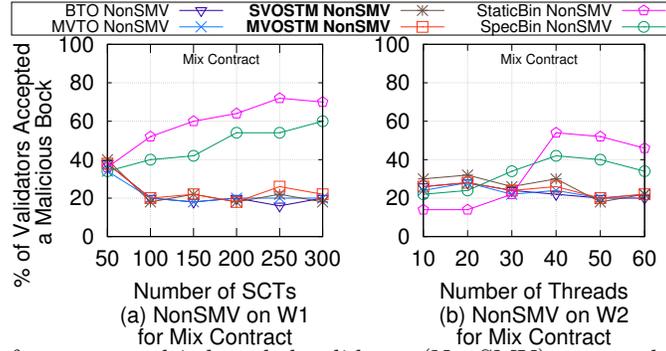


Fig. 3: % of average multi-threaded validator (NonSMV) accepted a malicious block for Mix Contract on W1 and W2

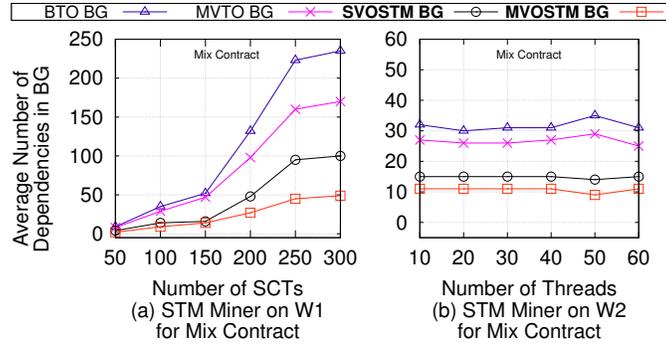


Fig. 4: Average Number of Dependencies in BG for Mix Contract on W1 and W2

To solve this problem, we developed a Smart Multi-threaded Validator (SMV), which identifies the malicious miner (described in Section 3.4). We prove that the SMV detects malicious block with the help of *counter* and rejects it. In fact all the validators shown in Fig. 2 (c) & (d) are SMV based. Another advantage of SMV is that once it detects a malicious miner during the concurrent execution of SCTs, it can immediately reject the block and need not execute the remaining SCTs in the block thus saving time.

Appendix E presents additional experiments that cover the average number of dependencies in the BG and additional space required to store the BG into the block. In addition to W1 and W2, we consider a third workload, W3 in which the number of shared data-items varied from 100 to 600 while the number of threads, SCTs, and hash-table size is fixed to 50, 100, and 30, respectively. We have shown that the performance of SMV validators for Mix contract on W3 and several other experiments for all the benchmarks. We compared the time taken by the SMV and NonSMV. We analyzed the speedup of fork-join validator for all the three workloads. We showed the actual time (microseconds) taken by all the miners and validators on W1 for the aforementioned four smart contract benchmarks in Tables 4 - 11.

5 Conclusion and Future Directions

This paper presents a framework for the concurrent execution of smart contracts by miner and validator, which has achieved better performance using object semantics. In blockchains that follow order-execute model [6] such as Ethereum [3], Bitcoin [18], each Smart Contract Transaction (SCT) is executed in two different contexts: first by the multi-threaded miner to propose a block and later by the multi-threaded validator to verify the proposed block by the miner as part of the consensus. To avoid FBR errors, the miner on concurrent execution of SCTs capture the dependencies among them in the form of a BG as in [7,9]. The validator then re-executes the SCTs concurrently while respecting the dependencies recorded in the BG to avoid FBR errors.

The miner executes the SCTs concurrently using STMs that exploit the object semantics: Single-Version Object-based STM (SVOSTM) and Multi-Version Object-based STM (MVOSTM). The dependencies among the SCTs collected during this execution are used by the miner threads to construct the BG concurrently. Due to the use of object semantics, the number of edges in the BG is smaller, which benefits both miners and validators by enabling them to execute SCTs quickly in a concurrent setting.

Another interesting aspect that we considered in this paper is the issue of malicious miners. Suppose that in the BG approach, a malicious miner proposes an incorrect BG which does not have all the edges resulting in edge missing BG (EMB) error. With the bin-based approach, the miner could place the conflicting transactions in the concurrent bin [21] resulting in faulty bin (FBin) error. To handle malicious miner, we have proposed a smart multi-threaded validator (SMV) which can identify these errors and reject the corresponding blocks.

Proposed SVOSTM and MVOSTM miner achieve on average speedup of $3.41\times$ and $3.91\times$ over serial miner respectively. Proposed SVOSTM and MVOSTM decentralized validator outperform with an average speedup of $46.35\times$ and $48.45\times$ over serial validator, respectively on Ethereum smart contracts.

Future Directions: There are several directions for future work. A natural question is whether the size of BG can become an overhead. Currently, the average number of SCTs in a block is ≈ 100 in Ethereum. So, storing BG inside the block does not consume much space. The BG constructed by MVOSTMs has fewer dependencies as compared with state-of-the-art SCT execution as shown in Fig. 4. However, the number of SCTs in a block can increase over time and as a result the BG size can grow, and storing it will consume more space. Hence, constructing storage optimal BG is an interesting challenge. Or achieving the concurrent execution of SCTs correctly without incurring any extra storage overhead without compromising with the speedup will be another interesting direction. So, a related relevant question is what the optimal storage required for achieving the best possible speedup?

Another interesting research direction is optimizing power consumption. Nowadays, multi-core systems are ubiquitous while serial execution fails to harness the power of multiple cores. So, as discussed in the paper concurrent execution of

SCTs by invoking multiple threads on a multi-core system ensures better performance than serial. But, multi-threading on the multi-core system consumes more power. Additional power is consumed by the multiple miner and validator threads to propose and validate the blocks concurrently. Hence, we would like to explore trade-off between harnessing the number of cores and power consumption.

Finally, since *Ethereum Virtual Machine (EVM)* [3] does not support multi-threading, it is not possible to test the proposed approach on Ethereum. So, another research direction is to design multi-threaded EVM. We plan to test our proposed approach on other blockchains such as Bitcoin [18], EOS [2] which follow the order-execute model and support multi-threading.

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Appendix

This section is organized as follows:

Section No.	Section Name
Appendix A	Advantage of OSTMs over RWSTMs
Appendix B	Remaining System Model
Appendix C	Detailed Proposed Mechanism
Appendix D	Correctness of BG, Multi-threaded Miner and Validator
Appendix E	Detailed Experimental Evaluation

A Advantage of OSTMs over RWSTMs

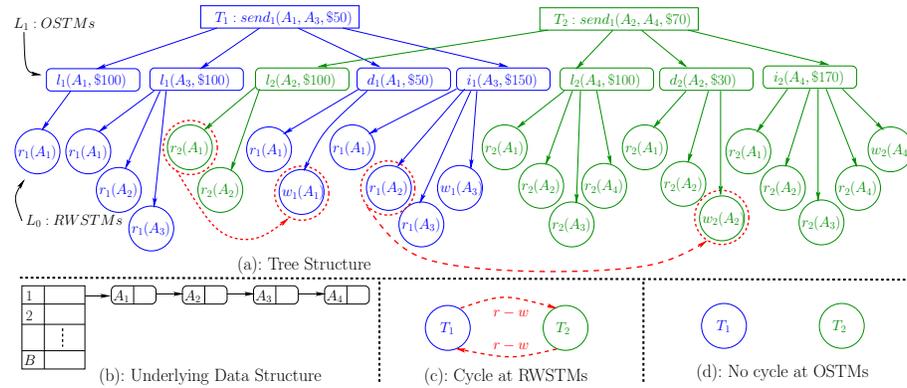


Fig. 5: Advantage of OSTMs over RWSTMs on SCTs

We now illustrate the advantage of OSTMs over RWSTMs. Consider an OSTM for hash-table which invokes the following methods: (1) `STM.begin()`, (2) `STM.lookup(k)` (or $l(k)$), (3) `STM.insert(k, v)` (or $i(k, v)$), (4) `STM.delete(k)` (or $d(k)$), and (5) `STM.tryC()` explained in Section 2

Consider Fig. 5, which demonstrates the advantage of OSTMs over RWSTMs while executing SCTs concurrently by multiple miner threads. Fig. 5 (a) shows two transactions T_1 and T_2 in the form of a tree structure which is working on a hash-table with B buckets. Fig. 5 (b) illustrates a bucket of the hash-table with four accounts (shared data-items) A_1, A_2, A_3 and A_4 which are accessed by these transactions. Accounts are stored in the form of a list. Thus to access account A_4 , a thread has to access A_1, A_2, A_3 before access it.

Suppose T_1 wants to send \$50 from account A_1 to A_3 and T_2 wants to send \$70 from account A_2 to A_4 . Before performing these transfers, the respective SCTs verify that each account has sufficient balance. After checking, the SCT T_1 deletes \$50 from A_1 and adds it to A_3 . At a lower-level, these operations involve reading and writing to both accounts A_1 and A_3 . The execution is shown in Fig. 5 (a) in form of a tree following the notation used by Weikum et al. [23, Chap 6]. Here, level 0 (or L_0) shows the operations as read and write while L_1 shows higher-level operations insert, delete and lookup.

Consider the execution at L_0 of Fig. 5 (a). The dotted red circles represent conflicting operations: $r_2(A_1)$ conflicts with $w_1(A_1)$ while $r_1(A_2)$ conflicts with

$w_2(A_2)$. As a result, this execution cannot be serialized as we cannot find any equivalent serial schedule because of cyclic conflict among T_1 and T_2 as shown in Fig. 5 (c). Hence for serializability [19] (or opacity [10]) either T_1 or T_2 has to abort. However, execution at level L_1 depicts that both transactions are working on different accounts and the higher-level methods (insert and lookup) are isolated. So, we can prune [23, Chap 6] this tree and isolate the transaction executions [20] at the higher-level with equivalent serial schedule T_1T_2 or T_2T_1 as shown in Fig. 5 (d). Essentially not all the conflicts of lower-level or read-write level matter at higher-level. In a typical execution, *object-conflicts* (or *oconflicts*) [20] are fewer than *read-write conflicts* (or *rwconflicts*). Therefore, OSTMs provides greater concurrency while reducing the number of aborts than RWSTMs.

B Remaining System Model

This section describes the remaining execution model and the notions of STMs used in this paper.

History: It is a sequence of invocations and responses of different transactional methods. In other words, a *history* [17,19] H is a sequence of events represented as $evts(H)$. H internally invokes multiple transactions by multiple threads concurrently. Each transaction calls higher-level methods, and each method comprises of read/write events. Here, we consider *sequential history* in which invocation on each transactional method follows the immediate matching response. It helps to make each transactional method as an atomic event. We denote the total order of the transactional method as \langle_H , so history is represented as $\langle evts(H), \langle_H \rangle$.

In this paper, we consider only *well-formed* histories in which a new transaction will not begin until the invocation of previous transaction has not been committed or aborted. History H comprises of the set of transactions as $txns(H)$. The set of *committed* and *aborted* transactions in H is denoted as $committed(H)$ and $aborted(H)$ respectively. So, the set of *incomplete* or *live* transactions in H is represented as $H.incomp = H.live = (txns(H) - committed(H) - aborted(H))$. **Transaction Real-Time Order:** Consider two transactions $T_i, T_j \in txns(H)$, if T_i terminates, i.e. either committed or aborted before $STM_begin_j()$ of T_j then T_i and T_j respects real-time [19] order represented as $T_i \prec_H^{RT} T_j$.

MVSR, VSR, and CSR: A history H is in *Multi-Version View Serializable* (or *MVSR*) [23, Chap. 5], if there exists a serial history S such that S is multi-version view equivalent to H . It keeps multiple versions with respect to each key. A history H is in *View Serializable* (or *VSR*) [23, Chap. 3], if there exists a serial history S such that S is view equivalent to H . It has shown that verifying the membership of MVSR and VSR in the database is NP-Complete [19]. So, researchers came across with an efficient equivalence notion which is *Conflict Serializable* (or *CSR*) [23, Chap. 3]. It is a sub-class of VSR which uses conflict graph characterization to verify the membership in polynomial time. A history

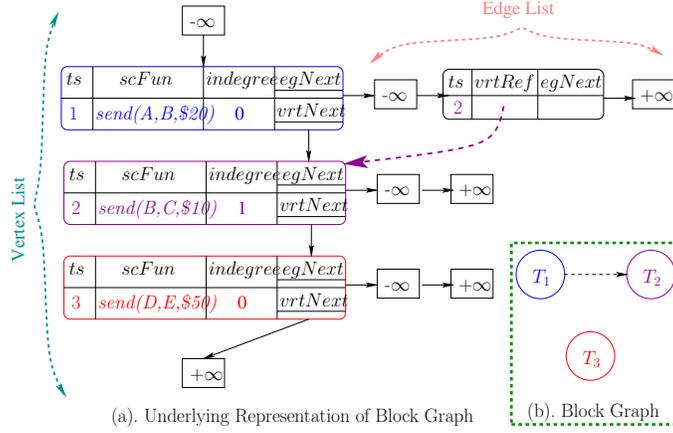


Fig. 6: Construction of Block Graph

H is in CSR if there exists a serial history S such that S is conflict equivalent to H .

Serializability and Opacity: Serializability[19] is a popular correctness criteria in databases. But it considers only *committed* transactions. This property is not suitable for STMs. Hence, Guerraoui and Kapalka propose a new correctness criteria opacity [10] for STMs which considers *aborted* transactions along with *committed* transactions as well. A history H is opaque [10,11], if there exist an equivalent serial history S with (1) set of events in S and complete history of H are same (2) S satisfies the properties of legal history and (3) The real-time order of S and H are preserved.

Linearizability: A linearizable [15] history H has the following properties: (1) In order to get a valid sequential history, the invocation and response events can be reordered. (2) The obtained sequential history should satisfy the sequential specification of the objects. (3) The real-time order should respect in sequential reordering as in H .

Lock Freedom: It is a non-blocking progress property in which if multiple threads are running for a sufficiently long time, then at least one of the threads will always make progress. Lock-free [14] guarantees system-wide progress, but individual threads may starve.

C Detailed Proposed Mechanism

This section describes the data structure and methods of concurrent BG in Appendix C.1. Then we describe the data structure of SVOSTM and MVOSTM in Appendix C.2. Later, we describes the execution of SCTs by Multi-threaded Validator rely on the BG provided by the miner in Appendix C.3 and detection of malicious miner by *Smart Multi-threaded Validator* in Appendix C.4.

C.1 Data Structure of the Block Graph

We use *adjacency list* to maintain the Block Graph $BG(V, E)$ inspired from [7,8]. Here V is the set of vertices (*vrtNodes*) is stored as a vertex list (*vrtList*). Similarly E is the set of Edges (*egNodes*) is stored as edge list (*egList* or conflict list) as shown in the Fig. 6 (a), both *vrtList* and *egList* store between the two sentinel nodes $Head(-\infty)$ and $Tail(+\infty)$. Each *vrtNode* maintains a tuple: $\langle ts, scFun, indegree, egNext, vrtNext \rangle$. Here, ts is the unique timestamp i of the transaction T_i to which this node corresponds to. $scFun$ is the smart contract function executed by the transaction T_i which is stored in *vrtNode*. The number of incoming edges to the transaction T_i , i.e. the number of transactions on which T_i depends, is captured by *indegree*. Field *egNext* and *vrtNext* points the next *egNode* and *vrtNode* in the *egList* and *vrtList* respectively.

Each *egNode* of T_i similarly maintains a tuple: $\langle ts, vrtRef, egNext \rangle$. Here, ts stores the unique timestamp j of T_j which has an edge coming from T_i in the graph. BG maintains the conflict edge from lower timestamp transaction to higher timestamp transaction. This ensures that the block graph is acyclic. The *egNodes* in *egList* are stored in increasing order of the ts . Field *vrtRef* is a *vertex reference pointer* which points to its own *vrtNode* present in the *vrtList*. This reference pointer helps to maintain the *indegree* count of *vrtNode* efficiently.

Fig. 6 (b) demonstrates the high level overview of BG which consist of three transaction T_1, T_2 and T_3 . Here, T_1, T_2 are in conflict while T_3 is independent. The underlying representation of it illustrated in Fig. 6 (a). For each transactions (T_1, T_2 and T_3) there exists a *vrtNode* in the *vrtList* of BG along with their conflicts. Since there is an edge from T_1 to T_2 , an *egNode* corresponding to T_2 is in the *egList* of T_1 . As mentioned earlier, the conflict edges go from lower timestamp to higher timestamp to ensure acyclicity of the block graph. After adding the *egNode*, the *indegree* of the *vrtNode* of T_2 in the *vrtList* is incremented as shown in Fig. 6 (a).

Block Graph Library Methods Accessed by Multi-threaded Miner:

Multi-threaded miner uses multiple threads to build the block graph. Specifically, the multi-threaded miner uses two methods to build the block graph: *addVertex()* and *addEdge()*. These two methods are *lock-free* [14]. Here, *addVertex(i)*, as the names suggests adds a *vrtNode* with $ts = i$ for respective *scFun* to the *vrtList* of the BG if such a vertex is not already present. This node is atomically added to *vrtList* using CAS operations.

The *addEdge(u, v)* method creates an *egNode* for v in u 's *vrtNode* if it does not already exist. First, it identifies the *egNode* in the *egList* of *vrtNode*. If *egNode* does not exist then it creates the node and adds into the *egList* of *vrtNode* atomically using CAS. The edges from u to v captures the conflicts between these transactions. This implies that v is dependent on u and the *scFun* of v has to be executed only after u 's execution.

Block Graph Library Methods Accessed by Multi-threaded Validator:

Multi-threaded validator uses multiple threads to re-executes the SCTs concurrently and deterministically with the help of BG given by the multi-threaded miner. To execute the SCTs, validator threads use three methods of block graph

library: *globalSearch()*, *remExNode()* and *localSearch()*. First a validator thread Th_i invokes the *globalSearch()* method which searches for a *vrtNode* n in the block graph having *indegree* 0 (i.e., source node). Such a node corresponds to a SCT, which does not depend on other transactions and hence can be executed independently without worrying about synchronization issues. On identifying n , Th_i atomically tries to claim it if not already claimed by some other thread. It does this by performing a CAS operation on the *indegree* to -1. After successful execution of *scFun* of n , Th_i invokes *remExNode* method which decrements the *inedgree* count for all the nodes which have an incoming edge from n . This list of nodes is maintained in the *egList* of n .

While decrementing the *indegree* count of conflicting nodes if the validator thread Th_i finds any other *vrtNode* with the *indegree* as 0 then it adds that a reference to that node in its thread-local log *thLog_i*. The *thLog_i* is used for optimization so that Th_i needs not to search in the global BG to find the next source node. If a reference to the source node exists in the local log of validator, it is identified by the *localSearch()* method. Th_i on identifying such a node n , atomically claims n (if not already claimed by another thread). Then it executes the *scFun* of n and then *remExNode* as explained above. A detailed description of BG methods, along with pseudocode is as follows:

BG(vrtNode, STM): Miner builds a BG based on *oconflict* given by the STM for all SCTs. BG takes the *oconflict* from the STM at Line 29 for *vrtNode* of SCT. If T_i have a conflict with T_j then it adds both SCT *vrtNode* in the BG at Line 32 and Line 33 using *addVertex()*. To maintain the dependency among the SCT T_i and T_j , the conflict edge goes from lower timestamp transaction (T_i) to higher timestamp transaction (T_j) to avoid the deadlock. It adds an edge using *addEdge()* at Line 35 or Line 37.

Algorithm 2 *BG(vrtNode, STM)*

```

27: procedure BG(vrtNode, STM)
28:   /*STM provides conflictList of committed transaction  $T_i$ */
29:   conflict = STM_getConflictList(vrtNode.tsi);
30:   /* $T_i$   $T_j$  are in conflict and  $T_j$  exists in conflict list of  $T_i$ */
31:   for all ( $ts_j \in$  conflict) do
32:     addVertex(tsj);
33:     addVertex(vrtNode.tsi);
34:     if ( $ts_j > vrtNode.ts_i$ ) then
35:       addEdge(vrtNode.tsi, tsj);
36:     else
37:       addEdge(tsj, vrtNode.tsi);
38:     end if
39:   end for
40: end procedure

```

addVertex(ts_i): This BG method is called by the multi-threaded miner. First, it identifies the correct location of *vrtNode* for transaction T_i in the BG at Line 42. If *vrtNode* is not exist in BG then it creates a *vrtNode* node of T_i at Line 44. Finally, It adds the *vrtNode* of transaction T_i in the *vrtList*[] of BG atomically at Line 45 with the help of *compare and swap* operation. If CAS fails then *addVertex()* again identifies the location of *vrtNode* node in the *vrtList*[] with the help of current vertex predecessor node (*vrtpred*) at Line 50. Eventually, *vrtNode* will be the part of BG. This method of the BG is *lock-free*.

Algorithm 3 *addVertex*(ts_i)

```
41: procedure addVertex( $ts_i$ )
42:   Search  $\langle vrtPred, vrtCurr \rangle$  of  $vrtNode$  of  $ts_i$  in  $vrtList[]$  of  $BG$ ;
43:   if ( $vrtCurr.ts_i \neq vrtNode.ts_i$ ) then
44:     Create new BG Node (or  $vrtNode$ ) of  $ts_i$  in  $vrtList[]$ ;
45:     if ( $vrtPred.vrtNext.CAS(vrtCurr, vrtNode)$ ) then
46:       /* $vrtNode$  successfully added in  $vrtList[]$ */
47:       return(Vertex added);
48:     end if
49:     /*Start with current  $vrtPred$  to search the new  $\langle vrtPred, vrtCurr \rangle$ */
50:     goto Line 42;
51:   else
52:     /* $vrtNode$  is already exist in  $vrtList[]$ */
53:     return(Vertex already exist);
54:   end if
55: end procedure
```

addEdge($conflictNode_1, conflictNode_2$): This BG method is called by the concurrent miner. First, It identifies the location of $conflictNode_2$ in the $egList[]$ of $conflictNode_1$ at Line 57. If $egNode$ of $conflictNode_2$ is not part of BG then it creates a $egNode$ at Line 59. Atomically, it adds an $egNode$ in the $egList[]$ of $conflictNode_1$ with the help of CAS at Line 60. After successful addition of $egNode$ it increments the *indegree* atomically with the help of $egNode.vrtRef$ pointer to maintain the dependency of it at Line 61. If CAS fails than *addEdge*() again identifies the location of $egNode$ node in the $egList[]$ with the help of current edge predecessor node ($egPred$) at Line 66. Eventually, $egNode$ will be the part of BG. This method of the BG is *lock-free*.

Algorithm 4 *addEdge*($conflictNode_1, conflictNode_2$)

```
56: procedure addEdge( $conflictNode_1, conflictNode_2$ )
57:   Search  $\langle egPred, egCurr \rangle$  of  $conflictNode_2$  in  $egList[]$  of the  $conflictNode_1$  vertex in  $BG$ ;
58:   if ( $egCurr.ts_i \neq conflictNode_2.ts_i$ ) then
59:     Create new BG Node (or  $egNode$ ) in  $egList[]$ ;
60:     if ( $egPred.egNext.CAS(egCurr, egNode)$ ) then
61:       Increment the indegree atomically of  $egNode.vrtRef$  in  $vrtList[]$ ;
62:       /* $conflictNode_2$  is successfully inserted*/
63:       return(Edge added);
64:     end if
65:     /*Start with current  $egPred$  to search the new  $\langle egPred, egCurr \rangle$ */
66:     goto Line 59;
67:   else
68:     /* $conflictNode_2$  is already exist in  $egList[]$ */
69:     return(Edge already present);
70:   end if
71: end procedure
```

localSearch($thlog_i$): This BG method is called by the multi-threaded validator. Validator thread identifies the source node in threads local log $thLog_i$ at Line 73. If it finds any source node in $thLog_i$ then it claims that node and atomically sets its *indegree* field to -1 so that no other multi-threaded validator threads claim this node at Line 74. After claiming of source node it executes smart contract function (associated with the identified source node) using *executeScFun*() at Line 77.

globalSearch(BG): The multi-threaded validator calls this BG method. Validator thread identifies the source node (with *indegree* 0) in BG at Line 86. If it finds

Algorithm 5 *localSearch*(*thlog_i*)

```
72: procedure localSearch(thlogi)
73:   Identify local log vertex(llVertex) with indegree 0 in thLogi.
74:   if (llVertex.indegree.CAS(0, -1)) then
75:     sctCount ← sctCount.get&Inc();
76:     /*Concurrently execute SCT corresponds to llVertex*/.
77:     executeScFun(llVertex.scFun).
78:     return( llVertex );
79:   else
80:     return(nil);
81:   end if
82: end procedure
```

any source node in BG, then it claims that node and atomically sets its *indegree* field to -1 so that no other multi-threaded validator threads claim this node at Line 87. After claiming of source node it executes smart contract function (associated with the identified source node) using *executeScFun()* at Line 90.

Algorithm 6 *globalSearch*(BG)

```
83: procedure globalSearch(BG)
84:   vrtNode ← BG.vrtHead; /*Start from the Head of the list*/
85:   /*Identify the vrtNode with indegree 0 in BG*/
86:   while (vrtNode.vrtNext ≠ BG.vrtTail) do
87:     if (vrtNode.indegree.CAS(0, -1)) then
88:       sctCount ← sctCount.get&Inc();
89:       /*Concurrently execute SCT corresponds to Node*/.
90:       executeScFun(vrtNode.scFun).
91:       return(vrtNode);
92:     end if
93:     vrtNode ← vrtNode.vrtNext;
94:   end while
95:   return(nil);
96: end procedure
```

remExecNode(removeNode): This BG method is called by the multi-threaded validator. It atomically decrements the *indegree* for each conflicting node of source node with the help of vertex reference pointer (*vrtRef*) at Line 99. *vrtRef* pointer helps to decrement the *indegree* count of conflicting node efficiently because thread need not to travels from head of the *vrtList*[] to identify the *vrtNode* node for decrementing the *indegree* of it. With the help of *vrtRef*, it directly decrements the *indegree* of *vrtNode*. While decrementing the *indegree* of *vrtNode* if it identifies the new source node than it keeps that node information in thread local log *thLog_i* at Line 101.

Algorithm 7 *remExecNode*(*removeNode*)

```
97: procedure remExecNode(removeNode)
98:   while (removeNode.egNext ≠ removeNode.eTail) do
99:     Atomically decrement the indegree of conflicting node using removeNode.vrtRef pointer.
100:    if (removeNode.vrtRef.indegree == 0) then
101:      Add removeNode.vrtRef node into thLogi.
102:    end if
103:    removeNode ← removeNode.egNext.vrtRef;
104:  end while
105:  return(nil);
106: end procedure
```

executeScFun(*scFun*): It executes the SCTs concurrently without the help of concurrency control protocol. First, it identifies the smart contract function (sc-

Fun) steps and executes them one after another at Line 109. If the current step (curStep) is lookup on key k , then it lookup the shared data item for key k from the shared memory at Line 112. If curStep is insert on key k with value as v , then it inserts the shared data item of key k with value v in the shared memory at Line 114. If curStep is delete on key k , then it deletes the shared data item of key k from the shared memory at Line 116. All these curStep of scFun can run concurrently with the other validator threads because only non-conflicting transactions will execute concurrently with the help of BG given by the multi-threaded miner.

Algorithm 8 *executeScFun*(scFun)

```

107: procedure executeScFun(scFun)
108:   while (scFun.steps.hasNext()) do /*scFun is a list of steps*/
109:     curStep = scFun.steps.next(). /*Get next step to execute*/
110:     switch (curStep) do
111:       case lookup( $k$ ):
112:         Lookup  $k$  from a shared memory.
113:       case insert( $k, v$ ):
114:         Insert  $k$  in shared memory with value  $v$ .
115:       case delete( $k$ ):
116:         Delete  $k$  from shared memory.
117:       case default: curStep is not lookup, insert and delete;
118:     end while
119:   return  $\langle void \rangle$ 
120: end procedure

```

C.2 Data Structure of SVOSTM and MVOSTM

This subsection describes the internal details about the data structure used to store shared data items in SVOSTM and MVOSTM.

As shown in Fig. 5 (b) of Appendix A, we have used a hash-table with a fixed size of buckets, where each bucket consists of a list of corresponding shared data items. The data structure used to store the data items depends on the protocol (SVOSTM, MVOSTM).

Data Structure of SVOSTM: Fig. 7 (a) demonstrates the structure of a shared data item in SVOSTM. Each shared data item consist of eight fields $\langle Account, val, Lock, max_L, max_U, cL_{list}[], cU_{list}[], next \rangle$. Where *Account* is a unique identifier which represents the shared data item or *key* or *account* (e.g., A_1), *val* field stores the value corresponding to data item. *Lock* is use to provide synchronization among the operations of different transactions working on same data items. *Lock* is acquired by the transaction before updating (inserting/deleting) the shared data item and released after the successful execution. Next two fields, i.e., max_L and max_U are counter variable

initialize as 0. Whenever a transaction performs any operation (STM.lookup()/STM.insert()/STM.delete()) on the shared data item, they update the corresponding value of the max_L/max_U . If current value of max_L/max_U is smaller than the timestamp of the transaction i then it updates max_L/max_U with the i . Otherwise, transaction with timestamp i returns abort and retry again. Field $cL_{list}[]$ and $cU_{list}[]$ store the timestamp of all committed transactions (transaction ids)

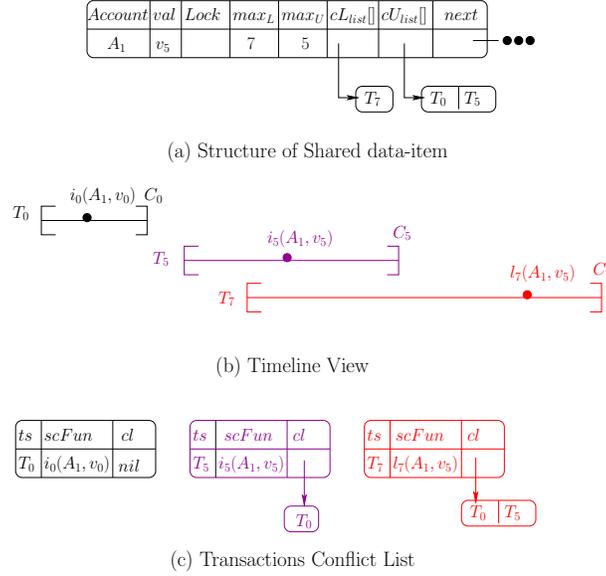


Fig. 7: Underlying Data Structure of Shared Data Items in SVOSTM

who has performed the `STM.lookup()` and update operations (`STM.insert()`/`STM.delete()`) on the shared data item respectively. These fields are used to generate the conflicts (dependencies) between the transactions. Finally, the `next` field is point to the next shared data item in the list of the respective bucket. The shared data item in the list of the corresponding bucket is stored in the increasing order of the keys.

To understand conflicts generation for concurrent execution of SCTs in SVOSTM, we consider three transactions T_0 , T_5 , and T_7 . In SVOSTM, a transaction T_i conflict with transaction T_j , if both are accessing a common data item k and at least one of them is update operation (insert or delete). The conflicts of SVOSTM is defined in Section 3.1.

Fig. 7 (b) shows the timeline view and respective operations of these transactions. Here, T_0 performed insert operation on shared data item as account A_1 with value v_0 (i.e., $i_0(A_1, v_0)$), and committed successfully. Therefore, the timestamp (ts) of T_0 is inserted in `cUlist` as shown in Fig. 7 (a). Similarly, T_5 , and T_7 are two concurrent execution performing insert (i.e., $i_5(A_1, v_5)$) and lookup (i.e., $l_7(A_1, v_5)$) operation respectively. Since T_5 performed insert on account A_1 , the `maxU` field is set to 5 and later it committed successfully so its transaction id T_5 is inserted in `cUlist`. Further, T_7 performed lookup on A_1 so `maxL` field is set to 7 and committed successfully so its transaction id T_7 is inserted in `cLlist`.

Fig. 7 (c) illustrates the transactions conflict list. As shown in the concurrent execution, T_0 is the first transaction, so it does not find any conflict with other transactions; hence, its conflict list is empty. Later, T_5 committed, so T_5 conflict list consists of T_0 since both T_0 and T_5 performed update operation on A_1 . A

transaction which performs update operation (insert or delete) conflicts with all the transactions present in both $cU_{list}[]$ and $cL_{list}[]$ lists corresponding to shared data item. At the commit time of T_5 , $cL_{list}[]$ was empty so, T_5 conflicts with T_0 only. Finally, transaction T_7 committed with the lookup on A_1 . A transaction which performs lookup operation, conflicts with all the transactions present in the $cU_{list}[]$ list. So, T_7 conflict list consists all the transactions present in $cU_{list}[]$ which is T_0 and T_5 . Hence, T_7 conflicts with T_0 and T_5 .

Data Structure of MVOSTM: SVOSTM stores only one version corresponding to each data item; however, MVOSTM maintains multiple versions. In the proposed framework, we have a fixed number of SCTs in each block, so we do not restrict the number of versions with each shared data item. Fig. 8 (a) shows the data structure used to store the shared data item in MVOSTM protocol. Here, each shared data item consists of four fields as $\langle Account, Lock, vl, next \rangle$. Where *Account*, *Lock*, and *next* field are same as defined earlier for SVOSTM. A new field *vl* stands for version list, which maintains version created by update operations (insert and delete) on the shared data item.

To store the versions of the shared data item, we used a list (*version list or vl*). Here, each entry of the version list consists of five fields $\langle ts, val, max_L, rvl, vNext \rangle$. It stores the version in increasing order of transaction's timestamps. The first field *ts* shows the timestamp of the transaction which created this version (see Fig. 8 (a)). The next field is *val*, which stores the value corresponding to that version. Field *max_L* is used to store the maximum id/ts of the transaction that has performed lookup on this version. A transaction T_i looks up from the version j such that j is *largest version timestamp* smaller than i . The *rvl[]* stands for *return value list*, which stores the timestamp of the committed transactions that have lookup from a particular version. Finally, the last field *vNext* is used to store a pointer to the next available version in the version list. As Fig. 8 (a) illustrates account A_1 maintains of three versions as 0, 5, and 10. *Version 0, 5, and 10* is created by transaction T_0 , T_5 , and T_{10} respectively.

Consider Fig. 8 (b) to understand conflicts generation in MVOSTM, which demonstrates the timeline view and respective operations of four transactions T_0 , T_5 , T_7 , and T_{10} . Here, transactions T_0 , T_5 , and T_{10} perform insert operation while T_7 performs a lookup on account A_1 . Due to insert operation by T_0 , T_5 , and T_{10} three different versions of account A_1 has been created, as shown in Fig. 8 (a). Here, transaction T_0 executed first, so it created version 0 and then T_5 performed insert operation ($i_5\langle A_1, v_5 \rangle$); therefore version 5 is created. After that T_7 performed lookup on A_1 which returns the value as v_5 (i.e., $l_7\langle A_1, v_5 \rangle$). After the successful commit of T_7 , it inserts its *ts* 7 in *max_L* of version 5 as shown in Fig. 8 (a). Here, transaction T_{10} began after the beginning of T_7 and committed before T_7 but still transaction T_7 is allowed to commit. Due to multiple versions, T_7 finds the older value of A_1 as v_5 created by T_5 and hence not abort; otherwise, in SVOSTM transaction T_7 has to return abort.

Fig. 8 (c) illustrates the conflict list of transactions. Here, T_0 is the first transaction and created version 0 of A_1 , so it does not conflict with any other transaction; hence, its conflict list is empty. Next, transaction T_5 , which created

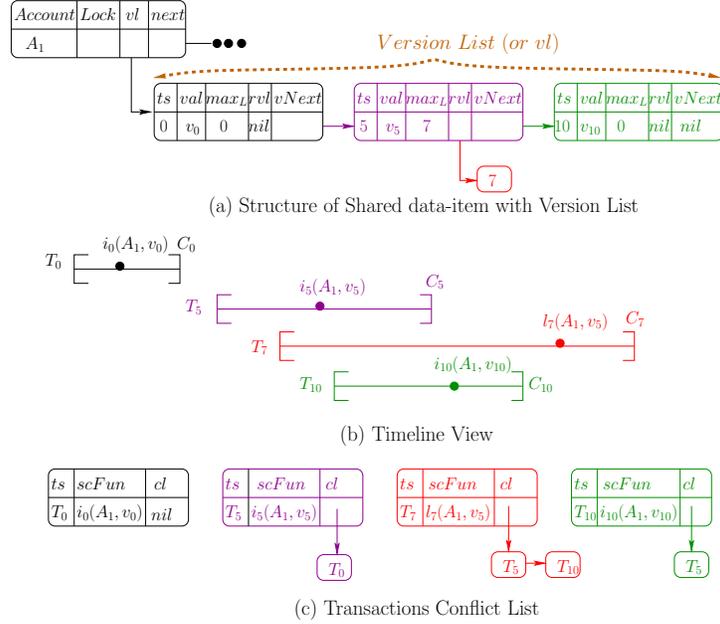


Fig. 8: Underlying Data Structure of Shared Data Items in MVOSTM

a new version of A_1 and committed successfully, so T_5 conflict list consists of T_0 . So, while generating conflict list, for an update (insert or delete) operation on account A_1 transaction first checks if the $rvl[]$ list is empty for the largest version smaller than its ts (transaction ts), then if the list is empty it adds that version ts in its conflict list otherwise adds all the ts in $rvl[]$ list of that version. For a lookup operation, a transaction adds the ts/id of the version which it has looked up and also the next version in the version list (if available) in its conflict list. Next is transaction T_{10} since it committed before T_7 , so in T_{10} conflict list, T_5 is added. The reason why only T_5 and not T_7 , this is because $rvl[]$ list consist only committed transaction ts and at the time when T_{10} committed T_7 was still live and not yet committed so $rvl[]$ of T_5 was empty. Finally, T_7 committed and as it performed a lookup on account A_1 from version 5, so it adds T_5 and the next version ts , which is T_{10} in its conflict list. Hence, T_7 conflicts with T_5 and T_{10} .

C.3 Multi-threaded Validator

Multi-threaded validator re-executes the SCTs concurrently and deterministically rely on the BG provided by the multi-threaded miner. To access the BG, validator uses *globalSearch()*, *localSearch()*, and *remExNode()* methods of block graph library. The descriptions of all these methods are given in Appendix C.1.

High level overview of Algorithm 9 shows the execution of SCTs by multi-threaded validator with the help of BG. First, multiple validator threads con-

currently identify the source node (*indegree* 0) in the BG using *globalSearch()* at Line 124. After identifying the source node, thread claims it (sets *indegree* to -1) atomically so that other multi-threaded validator threads can not claim it. Then it executes the *scFun* of SCT corresponding to the source node. After successful execution of *scFun*, it decrements the *indegree* count of conflicting node of source node using *remExNode()* at Line 125. While decrementing the *indegree* of conflicting node validator thread checks if it found new source node then it store that node in its thread local log *thLog* to execute next SCT at Line 127 efficiently.

Algorithm 9 Multi-threaded validator(*sctList*, BG): *v* threads concurrently and deterministically executes the SCTs using BG.

```

121: procedure Multi-threaded validator(sctList, BG)
122:   /*Execute until all the SCTs successfully completed*/
123:   while (sctCount < size_of(sctList)) do /*Initially, sctCount=0 to maintain count.*/
124:     vrtNode = globalSearch(BG); /*Identify the source node (indegree 0) in the BG*/
125:     remExecNode(vrtNode); /*Decrement the indegree of conflicting nodes*/
126:     while (thLog ≠ nil) do /*Identify source node in thread local log (thLog)*/
127:       vrtNode = localSearch(thLog);
128:       remExecNode(vrtNode);
129:     end while
130:   end while
131: end procedure

```

Finally, validator thread compares the FS_m given by the multi-threaded miner and FS_v computed by itself corresponding to each shared data item. If final state matches and proposed block reaches the global consensus, then it is added into the blockchain and respective miner awarded with the incentive.

C.4 Detection of Malicious Miner by Smart Multi-threaded Validator (SMV)

In this subsection, we propose a technique to detect malicious miner using *Smart Multi-threaded Validator*.

As we have seen the functionality of multi-threaded validator in Appendix C.3, it executes the SCTs concurrently rely on the BG provided by the multi-threaded miner. Suppose the miner that produces a block is malicious and does not add some edges to the BG. This can result in the blockchain systems entering inconsistent states due to *double spend*. We motivate this with an example. Consider three bank accounts A, B, C maintained on the blockchain with the current balance being \$100 in each of them. Now consider two SCTs T_i, T_j which are conflicting where (a) T_i transfers \$50 from A to B ; (b) T_j transfers \$60 from A to C . Considering the initial balance of \$100 in A account, both transactions cannot be executed.

If a malicious miner, say mm does not add an edge between these two transactions in the BG then both these SCTs can execute concurrently by validators. Then such execution could result in the final state with the balances in the accounts A, B, C as 40, 150, 160 respectively or 50, 150, 160. As we can see, neither of these final states can be obtained from any serial execution and are not correct states. Suppose the miner mm stores 40, 150, 160 for A, B, C in the

final state, and a validator v on concurrent execution arrives at the same state. Then, v will accept this block, which results in its state becoming inconsistent. If the majority of validators similarly accept this block, then the state of the blockchain essentially has become inconsistent. We denote this problem as *edge missing BG* or *EMB*.

Counter Based Solution to Catch the Malicious Miner: So, to avoid this issue, we propose a *Smart Multi-threaded Validator (SMV)*, which uses the concept of *counters* and identifies the malicious behavior of miner and rejects the proposed malicious block. Our algorithm is inspired by BTO in databases [23, Chap. 4]. SMV keeps track of each global data item that can be accessed across multiple transactions by different threads. Specifically, SMV maintains two global counters for each key of hash-table (shared data item) k - (a) $k.gUC$ (b) $k.gLC$. These respectively keep track of number of **updates** and **lookups** that are concurrently performed by different threads on k . Both these global counters are initialized to 0.

When a SMV thread Th_x is executing an SCT T_i then SMV similarly maintains two local variables corresponding to each global data item k which is accessible only by Th_x - (c) $k.lUC_i$ (d) $k.lLC_i$. These respectively keep track of number of updates and lookups performed by Th_x on k while executing T_i . These counters are initialized to 0 before the start of T_i .

Having described the counters, we will explain the high level design of SMV approach is shown in Algorithm 10. To access the BG, validator uses the block graph library methods *globalSearch()*, *localSearch()*, and *remExecNode()* as explained in Appendix C.1. Internally they use the *executeScFun()* method to execute the smart contract function (scFun). First, it identifies the scFun steps and executes them one after another at Line 132.

If current step (curStep) is lookup (at Line 135) on shared data-item key k then it checks the $k.gUC$ counter value. If $k.gUC$ counter value is not equal to $k.lLC$ at Line 136, that means another concurrent conflicting thread is also working on the same key k , i.e., conflict edge among them are missing in BG given by the miner. Then SMV reports the miner is malicious.

If $k.gUC$ counter value is zero means equal to $k.lLC$ then it atomically increments the $k.gLC$ counter of key k in shared memory at Line 137, so, any other concurrent conflicting thread checks the value as non zero it will detect the malicious miner. It also increments the local $k.lLC$ value by one at Line 138. Finally, validator thread lookups the key k from the shared memory and return the value as v at Line 139.

If curStep is insert on key k with value as v (at Line 143) then before inserting the key k with value v in the shared memory it checks both global counter values ($k.gLC == k.lLC$) && ($k.gUC == k.lUC$) at Line 144. If anyone of the counter value is not equal to corresponding to the local variable value, that means another concurrent conflicting thread is also working on the same key k , i.e., conflict edge among them is missing in BG given by the miner. Then SMV reports the miner is malicious.

If both global counter value is equal to corresponding local variables value, then it atomically increments the $k.gUC$ counter of key k in shared memory at Line 145, so, any other concurrent conflicting thread checks the value as non zero it will detect the malicious miner. It also increments the local $k.lUC$ value by one at Line 146. Finally, validator thread inserts the key k with value v in the shared memory at Line 147. Same things works if $curStep$ is deleted on key k at Line 151.

After successful execution of each $scFun$, thread atomically decrements $k.gUC, k.gLC$ by the value of $k.lUC_i, k.lLC_i$ respectively at Line 163. Then thread will reset $k.lUC_i, k.lLC_i$ to 0. Thus with the help of *counter*, validator threads are able to detect the malicious miner, and straightforward reject that block.

Algorithm 10 *executeScFun* ($scFun$): Execute the smart contract function ($scFun$) with atomic global lookup/update counter. Initially, *lookup counter* ($k.gLC$) and *update counter* ($k.gUC$) value is 0 corresponding to each shared data-items key k . Each transaction maintains local $k.lLC_i$ and local $k.lUC_i$ as 0 in transaction local log, $txLog$ corresponding to each key.

```

132: while (scFun.steps.hasNext()) do /*Assume that scFun is a list of steps*/
133:   curStep = scFun.steps.next(); /*Get the next step to execute*/
134:   switch (curStep) do
135:     case lookup(k):
136:       if (k.gUC == k.lLCi) then /*Check for update counter (uc) value*/
137:         Atomically increment the lookup counter, k.gLC;
138:         Increment k.lLCi by 1. /*Maintain k.lLCi in transaction local log txLog*/
139:         Lookup k from a shared memory;
140:       else
141:         return ⟨Miner is malicious⟩;
142:       end if
143:     case insert(k, v):
144:       if ((k.gLC == k.lLCi) && (k.gUC == k.lUCi)) then /*Check lookup/update counter
value*/
145:         Atomically increment the update counter, k.gUC;
146:         Increment k.lUCi by 1. /*Maintain k.lUCi in transaction local log txLog*/
147:         Insert k in shared memory with value v;
148:       else
149:         return ⟨Miner is malicious⟩;
150:       end if
151:     case delete(k):
152:       if ((k.gLC == k.lLCi) && (k.gUC == k.lUCi)) then /*Check lookup/update counter
value*/
153:         Atomically increment the update counter, k.gUC;
154:         Increment k.lUCi by 1. /*Maintain k.lUCi in transaction local log txLog*/
155:         Delete k in shared memory.
156:       else
157:         return ⟨Miner is malicious⟩;
158:       end if
159:     case default:
160:       curStep is not lookup, insert and delete;
161:       execute curStep;
162:   end while
163:   Atomically decrement the k.gLC and k.gUC corresponding to each shared data-item key k.

```

D Correctness of BG, Multi-threaded Miner and Validator

This section describes the proof of theorems stated for the correctness of BG, multi-threaded miner, and validator in Section 3. In order to define the cor-

rectness of BG, we identify the linearization points (LPs) of each method as follows:

1. $addVertex(vrtNode)$: ($vrtPred.vrtNext.CAS(vrtCurr, vrtNode)$) in Line 45 is the LP point of $addVertex()$ method if $vrtNode$ is not exist in the BG. If $vrtNode$ exist in the BG then ($vrtCurr.ts_i \neq vrtNode.ts_i$) in Line 43 is the LP point.
2. $addEdge(conflictNode_1, conflictNode_2)$: ($egPred.egNext.CAS(egCurr, egNode)$) in Line 60 is the LP point of $addEdge()$ method if $egNode$ is not exist in the BG. If $egNode$ is exist in the BG then ($egCurr.ts_i \neq conflictNode_2.ts_i$) in Line 58 is the LP point.
3. $localSearch(thLog)$: ($llVertex.indegree.CAS(0, -1)$) in Line 74 is the LP point of $localSearch()$ method.
4. $globalSearch(BG)$: ($vrtNode.indegree.CAS(0, -1)$) in Line 87 is the LP point of $globalSearch()$ method.
5. $remExecNode(removeNode)$: Line 99 is the LP point of $remExecNode()$ method.

Theorem 7. *The BG captures all the dependencies between the conflicting nodes.*

Proof. Section 3.1 represents the construction of BG by multi-threaded miner using SVOSTM and MVOSTM protocol. BG considers each committed SCT as a vertex and edges (or dependencies) depends on the used STM protocols such as SVOSTM and MVOSTM. So, the underlying STM protocol ensures that all the dependencies have been covered correctly among the conflicting nodes of BG. Hence, all the dependencies between the conflicting nodes are captured in the BG.

Theorem 8. *A history H_m generated by the multi-threaded miner with SVOSTM satisfies co-opacity.*

Proof. Multiple miner threads execute SCTs concurrently using SVOSTM and generate a concurrent history H_m . The underlying SVOSTM protocol ensures the correctness of concurrent execution of H_m . SVOSTM proves that any history generated by it satisfies co-opacity [20]. So, implicitly SVOSTM proves that the history H_m generated by multi-threaded miner using SVOSTM satisfies co-opacity.

Theorem 9. *A history H_m generated by a multi-threaded miner with MVOSTM satisfies opacity.*

Proof. In order to achieve the greater concurrency further, a multi-threaded miner uses the MVOSTM protocol, which maintains multiple versions corresponding to each shared data-item. MVOSTM ensures the correct concurrent execution of the history H_m with the equivalent serial history S_m . Any history generated by MVOSTM satisfies opacity [16]. So, implicitly MVOSTM proves that the history H_m generated by multi-threaded miner using MVOSTM satisfies opacity.

Theorem 10. *A history H_m generated by the multi-threaded miner with SVOSTM and history H_v generated by a multi-threaded validator are view equivalent.*

Proof. Multi-threaded miner execute the SCTs concurrently using SVOSTM protocol to propose a block and generates H_m along with BG. After that multi-threaded miner broadcasts H_m and BG to multi-threaded validators to verify the proposed block. Multi-threaded validator applies the topological sort on BG and obtained an equivalent serial schedule H_v . Since BG constructed from H_m while considering all the oconflicts and H_v obtained from the topological sort on BG. So, H_v will be equivalent to H_m . Similarly, H_v will also follow the *return value from* relation to H_m . Hence, H_v is legal. Since H_v and H_m , are equivalent to each other, and H_v is legal. So, H_m and H_v are view equivalent.

Theorem 11. *A history H_m generated by the multi-threaded miner with MVOSTM and history H_v generated by a multi-threaded validator are multi-version view equivalent.*

Proof. Following the proof of Theorem 10, multi-threaded miner executes H_m using MVOSTM and constructs the BG. MVOSTM maintains multiple-version corresponding to each shared data-item while executing the SCTs by multi-threaded miner. Later, multi-threaded validator obtained H_v by applying topological sort on BG given by miner. Since, H_v obtained from topological sort on BG so, H_v will be equivalent to H_m . Similarly, BG maintains the *return value from* relations of H_m . So, from MVOSTM protocol if T_j returns a value of the method for shared data-item k say $rv_j(k)$ from T_i in H_m then T_i committed before $rv_j(k)$ in H_v . Therefore, H_v is valid. Since H_v and H_m are equivalent to each other and H_v is valid. So, H_m and H_v are multi-version view equivalent.

Theorem 12. *Smart Multi-threaded Validator rejects malicious blocks with BG that allow concurrent execution of dependent SCTs.*

Proof. With the help of global counter *Smart Multi-threaded Validator (SMV)* identifies the concurrent execution of dependent SCTs at Line 136, Line 144, and Line 152 of Algorithm 10 and reject the malicious block. Detail description of SMV is available in Appendix C.4. We have tested our proposed counter-based approach with the existence of malicious block shown in Appendix E. SMV straightforward reject the malicious block and notify to the other nodes part of the network. Hence, SMV rejects malicious blocks with BG that allow concurrent execution of dependent SCTs.

E Detailed Experimental Evaluation

This section presents a detailed description of the benchmark contracts that we have considered in this paper. It also includes the additional experiments which show the performance benefits of proposed multi-threaded miner and validator over state-of-the-art miners and validators on various workloads. Along with this, we proposed *smart multi-threaded validator* to identify malicious miners.

Smart Contracts: Clients (possibly different) send transactions to the miners in the form of complex code known as smart contracts. It provides several complex services such as managing the system state, ensuring rules, or credentials checking of the parties involved. [9]. For better understanding, we have described *Coin*, *Ballot*, *Simple Auction* Smart Contracts from Solidity documentation [5]. We consider one more smart contract as *Mix Contract*, which is the combination of the three contracts as mentioned above in equal proportion and seems more realistic.

(1) *Coin Contract*: It is a sub-currency contract which implements simplistic form of a cryptocurrency and is used to transfer coins from one account to another account using *send()*, or used to check the account balance using *get_balance()* function. Accounts (unique addresses in Ethereum) are shared objects. A conflict will occur when two or more transaction consists of at least one common account, and one of them is updating the account balance.

Algorithm 11 shows the functionality of the coin contract, where *mint()*, *send()*, and *get_balance()* are the functions of the contract. These functions can be called by the miners or through other contracts. It initialized by the contract creator (or contract deployer) to a special public state variable *minter* (Line 165). Accounts are identified by Solidity mapping data structure essentially a $\langle key-value \rangle$ pair (Line 167), where a key is the unique Ethereum address and value is unsigned integer depicts the coins (or balance) in respective account. Initially, the contract deployer (aka *minter*) creates new coins and allocate it to each receiver (Line 173).

Further, *send()* function is used to transfer the coin from the sender account to the receiver account. The function ensures that the sender has sufficient balance in his account (Line 178). If sufficient balance found in the sender's account, the coin transferred from the sender account to the receiver account. By calling *get_balance()*, anyone can query the specific account balance (Line 183).

(2) *Ballot Contract*: This contract is used to organize electronic voting where voters and proposals are the shared objects and stored at unique Ethereum addresses. At the beginning of voting, the chairman of the ballot gives rights to voters to vote. Later, voters either delegate their vote to other voter using *delegate()* or directly vote to specific proposal using *vote()*. Voters are allowed to delegate or vote only once per ballot. A conflict will occur when two or more voters vote for the same proposal, or they delegate their votes to the same voter simultaneously.

(3) *Simple Auction Contract*: In this contract, an auction is conducted where a bidder places their bids. Here bidders, *maxBid*, *maxBidder*, and auction end time are the shared object which can be accessed by multiple threads. The auction will end when the bidding period (or end time) of the auction is over. The auction end time is initialized at the beginning by the auction master. A *bid()* function is used to bid the amount by a bidder for the auction. In the end, the bidder with the highest bid amount will be the winner, and all other bidders amount is then returned to them using *withdraw()*. A conflict will occur when more than two bidders try to bid using *bidPlusOne()* at the same time.

Algorithm 11 `Coin()`: A sub-currency contract used to depict the simplest form of a cryptocurrency.

```

164: procedure Coin()
165:   address public minter; /*Minter is a unique public address*/
166:   /*Map <key-value> pair of hash-table as <address-balance>*/
167:   mapping(address => uint) balances.
168:   Constructor() public
169:     minter = msg.sender. /*Set the sender as minter*/
170:   function mint(address receiver, uint amount )
171:     if (msg.sender == minter) then
172:       /*Initially, add the balance into receiver account*/
173:       balances[receiver] += amount.
174:     end if
175:   end function
176:   function send(address receiver, uint amount)
177:     /*Sender don't have sufficient balance*/
178:     if (balances[msg.sender] < amount) then return (fail);
179:     end if
180:     balances[msg.sender] -= amount;
181:     balances[receiver] += amount;
182:   end function
183:   function get_balance(address account)
184:     return (balance);
185:   end function
186: end procedure

```

(4) *Mix Contract*: In this contract, aforementioned smart contracts are executed simultaneously. This contract is designed to show real-time scenarios in which a block consists of SCTs from different contracts. For the experiment, we combined SCTs for three contracts in a block.

Performance Analysis: To analyze the proposed approach further, we show the performance analysis on remaining benchmark contracts and workloads. Additionally, we consider one more workload W3, in which the number of shared objects (data-items) vary from 100 to 600, while threads, SCTs, and hash-table size are fixed to 50, 100, and 30, respectively. For W3, with the increase in the number of shared objects, contention will decrease.

In Fig. 9 to Fig. 11 numbering (a), (b), (c) show the multi-threaded miner speedup over serial miner on W1, W2, and W3 for coin, ballot, and auction contract respectively. Further, (d), (e), (f) shows the smart multi-threaded validator speedup over serial validator on W1, W2, and W3 for the coin, ballot, and auction contract respectively. It shows that the speedup decreases for multi-threaded miner on W1; however, it increases on W2 on all benchmark contracts. The observation for W1 and W2 are the same as explained in Section 4. Finally, Fig. 12 (a) and Fig. 12 (b) shows the speedup for multi-threaded miner and SMV for mix contract on workload W3.

For W3, as shown in Fig. 9 (c), Fig. 10 (c), Fig. 11 (c), and Fig. 12 (a) the speedup increase for multi-threaded miner with increase in shared objects (contention decreases). However in mix contract (as shown in Fig. 12 (a)) small decrements for BTO and MVTO miner can be observed. Also, static bin miner is performing worse than serial due to the overhead of static conflict prediction before executing SCTs speculatively. Similarly Fig. 9 (f), Fig. 10 (f), Fig. 11 (f),

and Fig. 12 (b) shows the speedup achieved by SMV over serial validator on W3. The speedup of bin-based SMV is less than STM validator. Thus for the better visualization, we have shown speedup for STM validator on $y1$ axis whereas for bin-based SMV on $y2$ axis. As we can observe, MVOSTM SMV outperforms all other validators; however, performance decreases with increasing shared objects. **Dependencies in the BG:** Fig. 13 to Fig. 15 shows the average dependencies in the Block Graph (BG) generated by STM based multi-threaded miners for the coin, ballot, and auction contract on all workloads. While Fig. 16.(a) shows the average number of dependencies in the BG for mix contract on W3. There is no BG in bin-based static bin and speculative bin miner; instead, there is a sequential and concurrent bin. So from block size consideration, bin-based approach is efficient, though, from validator speedup consideration, STM based approach is better as shown in all smart multi-threaded validators figures.

As shown in figures for W1 with the increase in SCTs, the number of dependencies increases in BG. However, for W2, there is no much variation since we fixed the number of SCTs to 100 in W2. Moreover, the analysis of W3 is quite impressive. Here for the ballot and mix contracts with the increase in shared data items, the dependencies in BG increases for BTO and MVTO. However, it decreases for SVOSTM and MVOSTM as shown in Fig. 14 (c). Also, for coin contract, dependencies in BG decreases with an increase in shared data-item. In the Auction contract, it depends on the highest bid; if the highest bid is bided in the beginning, then there will be least dependencies in BG.

The average speedup (averaged across the workloads) achieved by the multi-threaded miners and smart multi-threaded validators on workload W1, W2, and W3 on all benchmarks are shown in Table 1 and Table 2 respectively. Note that the average speedup result shown in Section 4 for mix contract is averaged on workload W1 and W2.

Table 1: Overall Average Speedup on all Workloads by Multi-threaded Miner over Serial

Contract	Multi-threaded Miner					
	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner	SpecBin Miner	StaticBin Miner
Coin	1.596	1.959	4.391	5.572	1.279	6.689
Ballot	0.960	1.065	2.229	2.431	1.175	2.233
Auction	2.305	2.675	3.456	3.881	1.524	2.232
Mix	1.596	2.118	3.425	3.898	1.102	3.080
Total Avg. Speedup	<i>1.61</i>	<i>1.95</i>	<i>3.38</i>	<i>3.95</i>	<i>1.27</i>	<i>3.56</i>

Table 2: Overall Average Speedup on all Workloads by SMV over Serial

Contract	Smart Multi-threaded Validator (SMV)					
	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	SpecBin SMV	StaticBin SMV
Coin	26.576	28.635	30.344	32.864	5.296	7.565
Ballot	26.037	28.333	33.695	36.698	3.570	3.780
Auction	27.772	31.781	29.803	32.709	4.694	5.214
Mix	36.279	39.304	42.139	45.332	4.279	4.463
Total Avg. Speedup	<i>29.17</i>	<i>32.01</i>	<i>34.00</i>	<i>36.90</i>	<i>4.46</i>	<i>5.26</i>

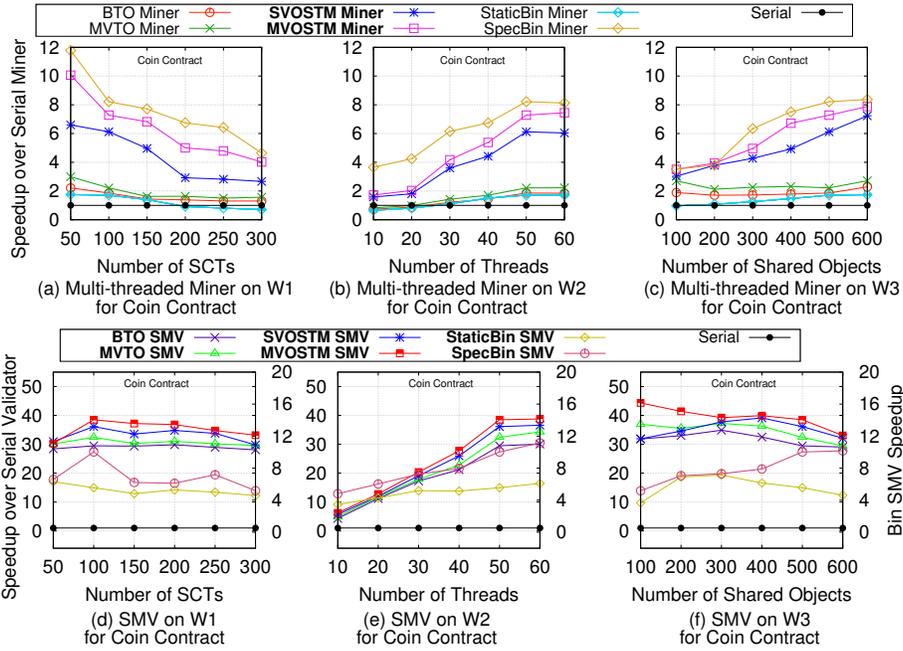


Fig. 9: Multi-threaded Miner and Smart Multi-threaded Validator Speedup Over Serial Miner and Validator Across all Workloads for Coin Contract

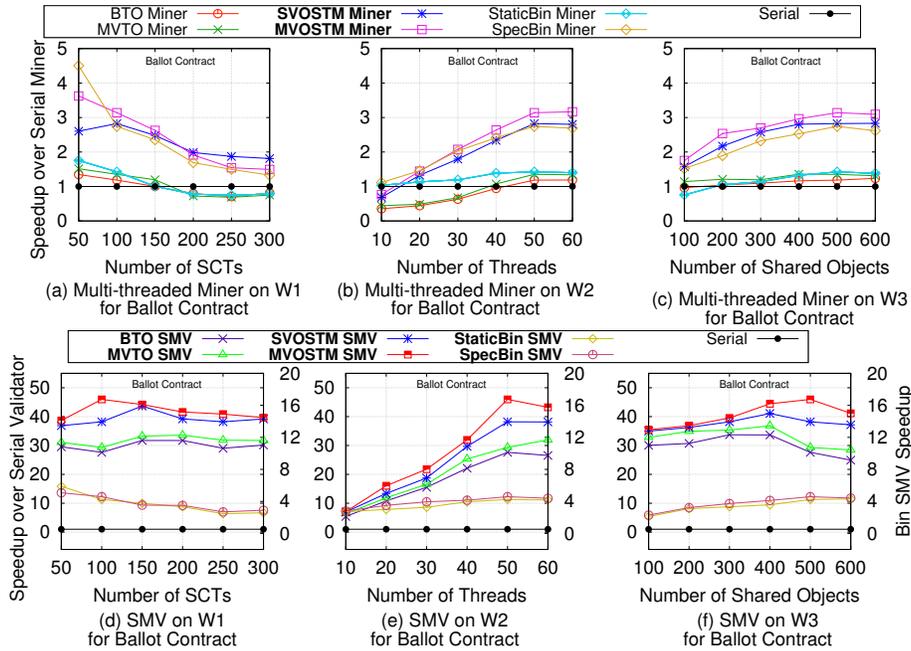


Fig. 10: Multi-threaded Miner and Smart Multi-threaded Validator Speedup Over Serial Miner and Validator Across all Workloads for Ballot Contract

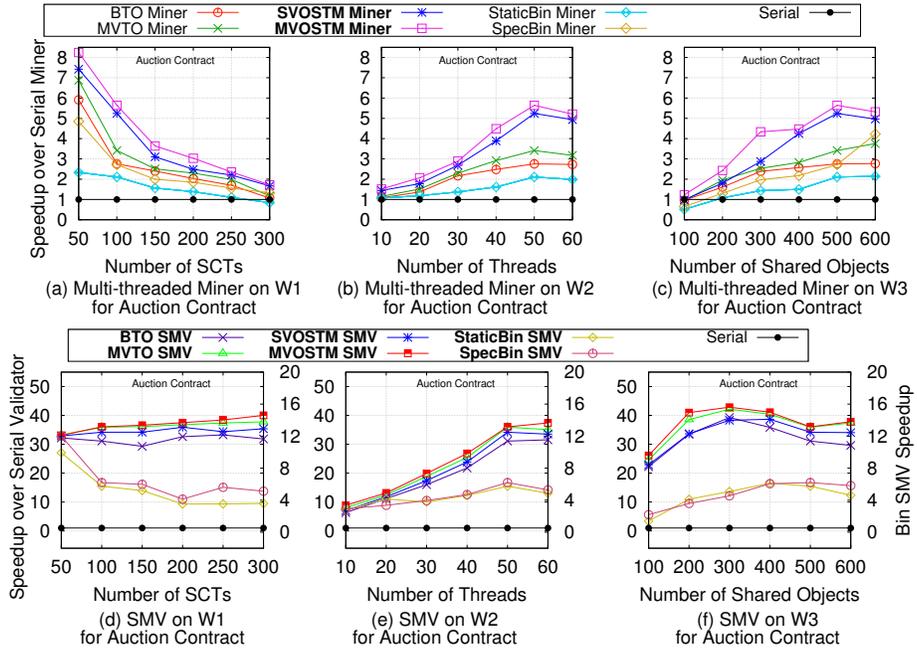


Fig. 11: Multi-threaded Miner and Smart Multi-threaded Validator Speedup Over Serial Miner and Validator Across all Workloads for Auction Contract

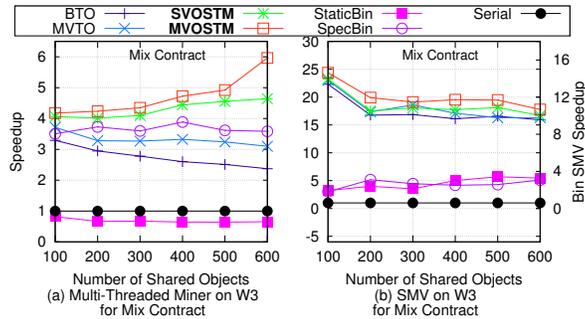


Fig. 12: Multi-threaded Miner and Smart Multi-threaded Validator Speedup Over Serial Miner and Validator on W3 for Mix Contract

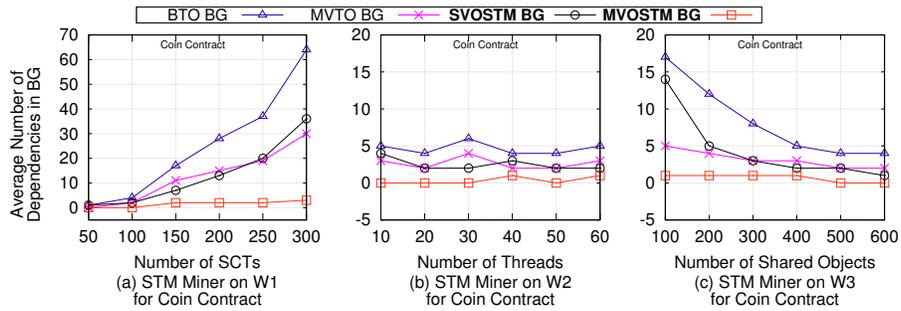


Fig. 13: Average Number of Dependencies in Block Graph for Coin Contract

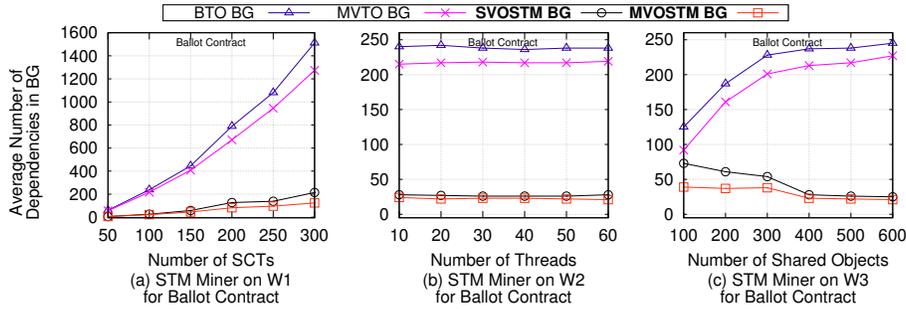


Fig. 14: Average Number of Dependencies in Block Graph for Ballot Contract

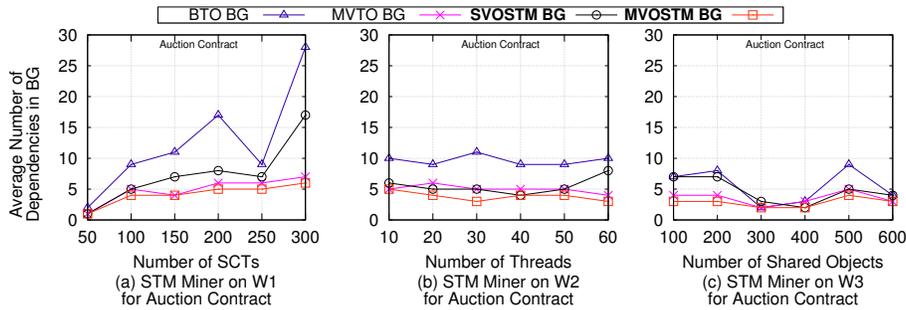


Fig. 15: Average Number of Dependencies in Block Graph for Auction Contract

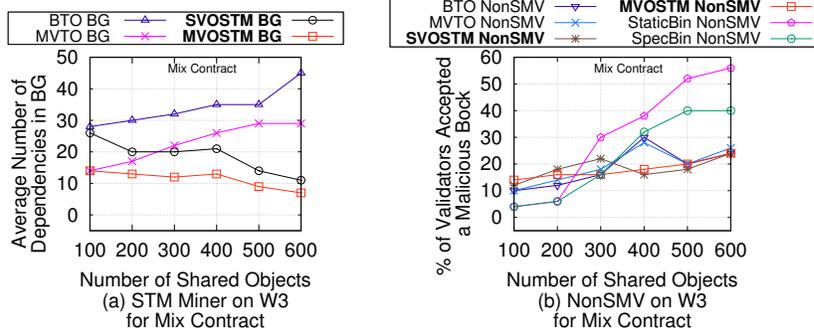


Fig. 16: Average Number of Dependencies in Block Graph and Percentage of Average Multi-threaded Validator (NonSMV) Accepted a Malicious Block on W3 for Mix Contract

Experiments on Malicious Miner: A multi-threaded validator deterministically executes the SCTs rely on the BG provided by the miner in the block. However, what if a miner is malicious and embeds an incorrect BG? To answer this question, we have done experiments for the malicious miner. As explained earlier, we proposed a *Smart Multi-threaded Validator (SMV)* to prevent such malicious activity due to concurrent execution of SCTs of the block. This experiment shows how many validators (NonSMV) accept malicious block proposed by a malicious miner.

To obtain the malicious miner activity, we generate two SCTs of double-spending (explained in Appendix C.4) in coin contract and ballot contract (double voting: a voter votes two different proposals with one voting right). After that, malicious miner added such SCTs into the block, manipulate the final state accordingly, but did not add the respective dependencies in BG, i.e., for these two SCTs, indegrees will be 0. Finally, malicious miner broadcast the malicious block in the network. Then multi-threaded NonSMV validators re-executes the SCTs concurrently using BG provided by the malicious miner. However, the validators may execute double-spending SCTs concurrently and compute the same final state as provided by the malicious miner. So, some of the validators accept the malicious block. If they reach a consensus, then they will add this malicious block into the blockchain. It may cause a severe issue in the blockchain.

Fig. 3, Fig. 16.(b), Fig. 17, and Fig. 18 demonstrates the average percentage of validators accepting a malicious block on different workloads and benchmark contracts. Here, we consider 50 validators and run the experiments for the Coin, Ballot, and Mix contract. So, we can conclude that if the malicious miner is present in the network, then some validators may agree on the malicious block, and harm the blockchain. Therefore, we should ensure the rejection of such a malicious block in the blockchain. To address this issue, we proposed *Smart Multi-threaded Validator* (describe in Appendix C.4), which always detects the malicious block at the time of concurrent execution of malicious SCTs (double-spending and double voting) with the help of *counter* and straightforward reject that block. Analysis of SMVs is presented for mix contract in Section 4 and other contracts at the beginning of this section.

So, the next obvious question is, how much extra time does *SMVs* is taking to serve the purpose of identifying the malicious miner over *NonSMVs*? We observe that the counter-based multi-threaded validator (i.e., Smart Multi-threaded Validator (SMV)) approach is giving a bit less speedup than without counter-based multi-threaded validator (i.e., NonSMV) however this decrement in speedup is very low on considered workloads. Instead of small decrement in speedup, it is evident to use counter-based multi-threaded validators (*SMVs*) to preserve the correctness of the blockchain.

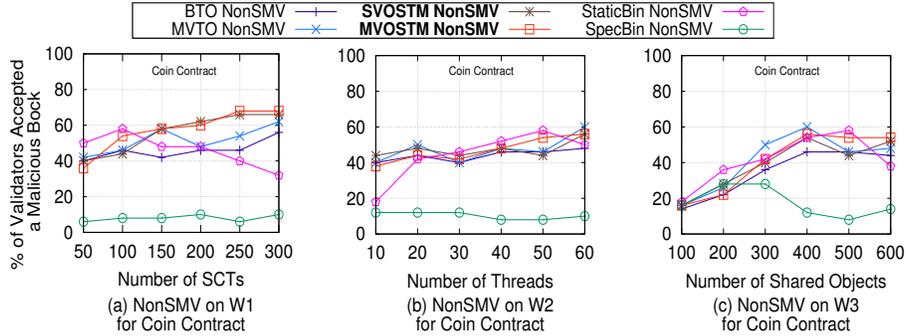


Fig. 17: Percentage of Average Multi-threaded Validator (NonSMV) Accepted a Malicious Block for Coin Contract

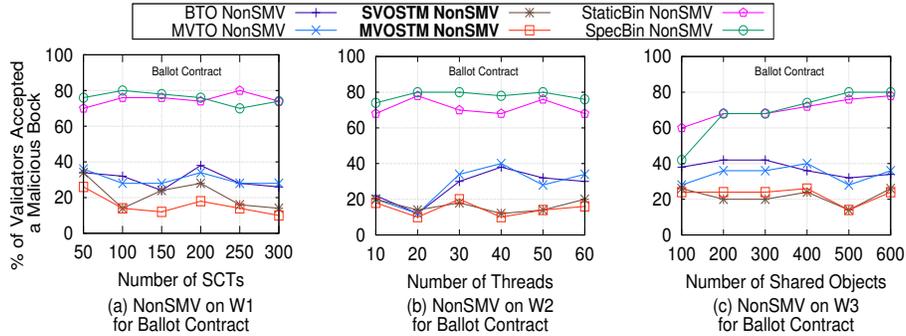


Fig. 18: Percentage of Average Multi-threaded Validator (NonSMV) Accepted a Malicious Block for Ballot Contract

Experiments on Block Graph Size: We also measure the additional space required to append the BG into the block. In Ethereum and Bitcoin average block size is ≈ 20.98 [4] and ≈ 1123.34 KB [1] respectively for the interval of 1st Jan. 2019 to 8th March 2020, which is keep on increasing every year. The average number of transactions in a block of Ethereum is ≈ 100 [4]. So, on an average, each transaction requires 0.2 KB (≈ 200 bytes) in Ethereum. Based on this simple calculation, we have computed block size with an increase in SCTs per block for workload W1. To compute the block size Equation 1 is used.

$$B = 200 * N_{SCTs} \quad (1)$$

Where, B is block size in bytes, N_{SCTs} number of smart contract transactions (SCTs) in block, and 200 is the average size of an SCT in bytes.

We use *adjacency list* to maintain the Block Graph $BG(V, E)$ inspired from [7,8]. Here V is the set of vertices (*vertNodes*) is stored as a vertex list, *vertList*. Similarly E is the set of Edges (*egNodes*) is stored as edge list (*egList* or conflict list) as shown in the Fig. 6 (a) of Appendix C.1. Both *vertList* and *egList* store between the two sentinel nodes $Head(-\infty)$ and $Tail(+\infty)$. Each *vertNode* maintains a tuple: $\langle ts, scFun, indegree, egNext, vrtNext \rangle$. Here, ts (an integer) is the

unique timestamp i of the transaction T_i to which this node corresponds to. $scFun$ (an integer) is the ID of smart contract function executed by the transaction T_i which is stored in $vrtNode$. The number of incoming edges to the transaction T_i , i.e. the number of transactions on which T_i depends, is captured by $indegree$ (an integer). Field $egNext$ (an address) and $vrtNext$ (an address) points the next $egNode$ and $vrtNode$ in the $egList$ and $vrtList$ respectively. So a vertex node V_s size is 28 bytes in the experimental system, which is sum of the size of 3 integer variables and 2 pointers.

Each $egNode$ of T_i similarly maintains a tuple: $\langle ts, vrtRef, egNext \rangle$. Here, ts (an integer) stores the unique timestamp j of T_j which has an edge coming from T_i in the graph. BG maintains the conflict edge from lower timestamp transaction to higher timestamp transaction. This ensures that the block graph is acyclic. The $egNodes$ in $egList$ are stored in increasing order of the ts . Field $vrtRef$ (an address) is a *vertex reference pointer* which points to its own $vrtNode$ present in the $vrtList$. This reference pointer helps to maintain the *indegree* count of $vrtNode$ efficiently. The $egNext$ (an address) is a pointer to next edge node, so edge node E_s requires a total of 20 bytes in the experimental system.

The experimental results on the percentage of additional space required to store BG in the block are shown in Fig. 19 to Fig. 22 for all benchmark contracts and workloads. The size of BG (β) in bytes is computed using *Equation 2*, while to compute the percentage of additional space (β_p) required to store BG in the block is calculated using *Equation 3*.

$$\beta = (V_s * N_{SCTs}) + (E_s * M_e) \quad (2)$$

Where, β is size of Block Graph (BG) in bytes, V_s is size of a vertex node of BG in bytes, N_{SCTs} are number of smart contract transactions (SCTs) in a block, E_s is size of a edge node in bytes of BG , and M_e is number of edges in BG .

$$\beta_p = (\beta * 100) / B \quad (3)$$

As shown in Fig. 19 to Fig. 22, it can be observed that with an increase in the number of dependencies, the space requirements also increase. The number of dependencies in the Ballot contract (Fig. 14 (a)) for $W1$ is higher compared to other contracts, so the space requirement is also high. In all the figures, the space requirements of BG by MVOSTM, SVOSTM is smaller than MVTO and BTO miner. The average space required for BG in % concerning block size is 14.24%, 14.95%, 21.20%, and 22.70% by MVOSTM, SVOSTM, MVTO, and BTO miner, respectively on $W1$ (As shown in Table 3). Since the number of dependencies in BG developed by MVOSTM is smaller than BG generated by other STM protocols, so it requires less space to store BG. In the future, we are planning to reduce space further to store the BG in the block by keeping the optimized or compressed BG.

Table 3: On W1 Average % Increase in Block Size due to BG in Ethereum

Contract	Average % of Increase in Block Size due to BG on W1			
	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner
Coin	14.225	13.702	13.712	13.220
Ballot	44.542	40.633	17.377	16.073
Auction	13.811	13.427	13.534	13.392
Mix	18.238	17.043	15.180	14.264
Total Avg. Change	22.70	21.20	14.95	14.24

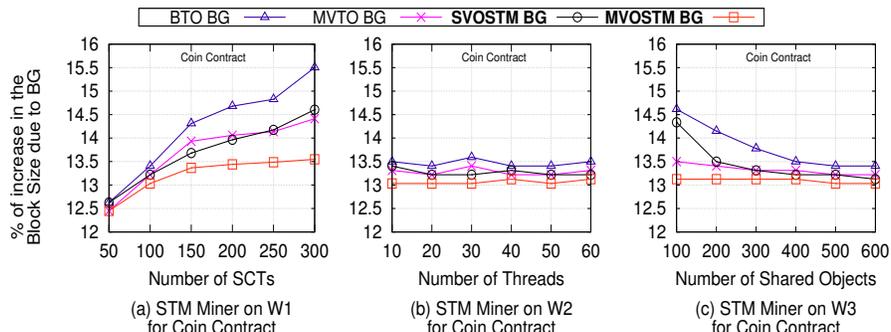


Fig. 19: Percentage of Additional Space Required to Store Block Graph (BG) in Ethereum Block for Coin Contract

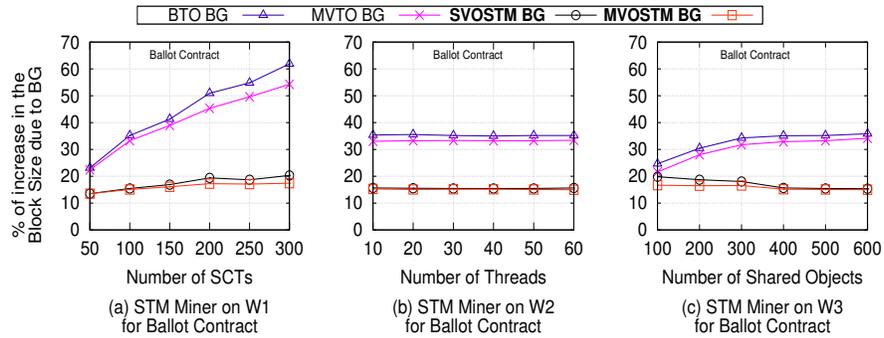


Fig. 20: Percentage of Additional Space Required to Store Block Graph (BG) in Ethereum Block for Ballot Contract

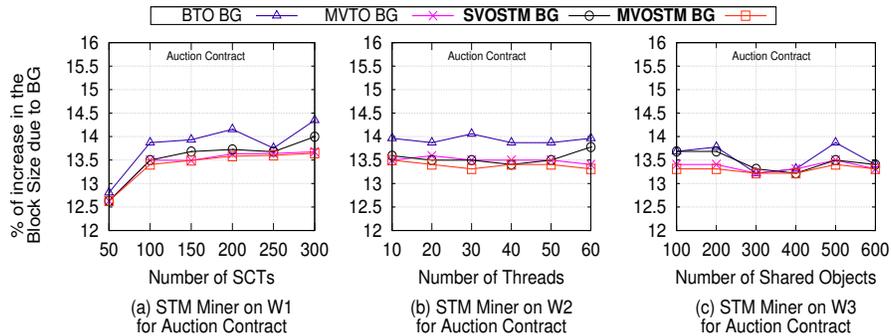


Fig. 21: Percentage of Additional Space Required to Store Block Graph (BG) in Ethereum Block for Auction Contract

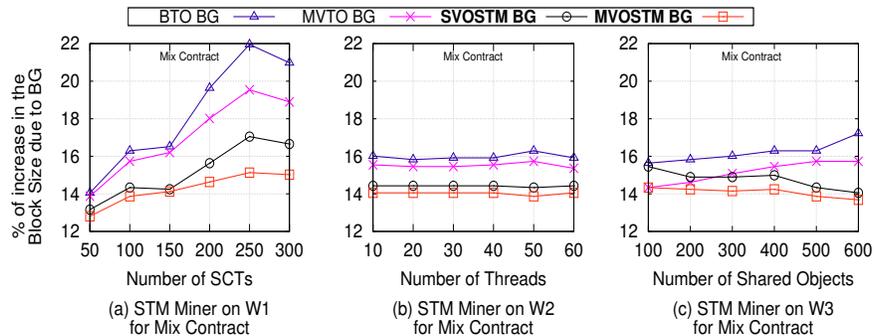


Fig. 22: Percentage of Additional Space Required to Store Block Graph (BG) in Ethereum Block for Mix Contract

Performance Analysis of Decentralized NonSMV Validator: Fig. 23 and Fig. 24 show the performance of Decentralized NonSMV validator. Here we can observe that average speedup achieved by decentralized NonSMV validator is slightly better than SMV including bin-based and fork-join validators. However, NonSMV validators are prone to accepting a malicious block (the acceptance of malicious block is shown in Fig. 3, Fig. 17, and Fig. 18).

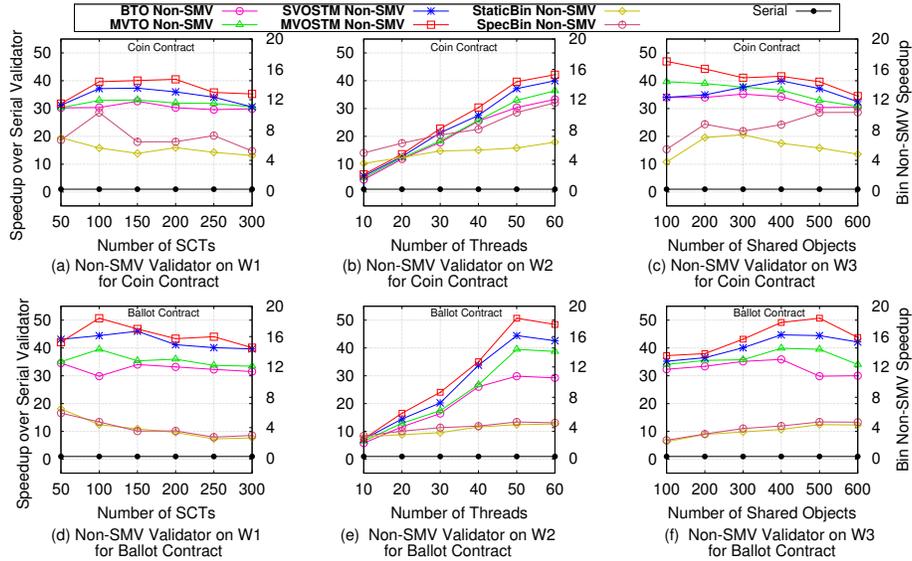


Fig. 23: Multi-threaded NonSMV Validator Speedup Over Serial Validator for Coin and Ballot Contract

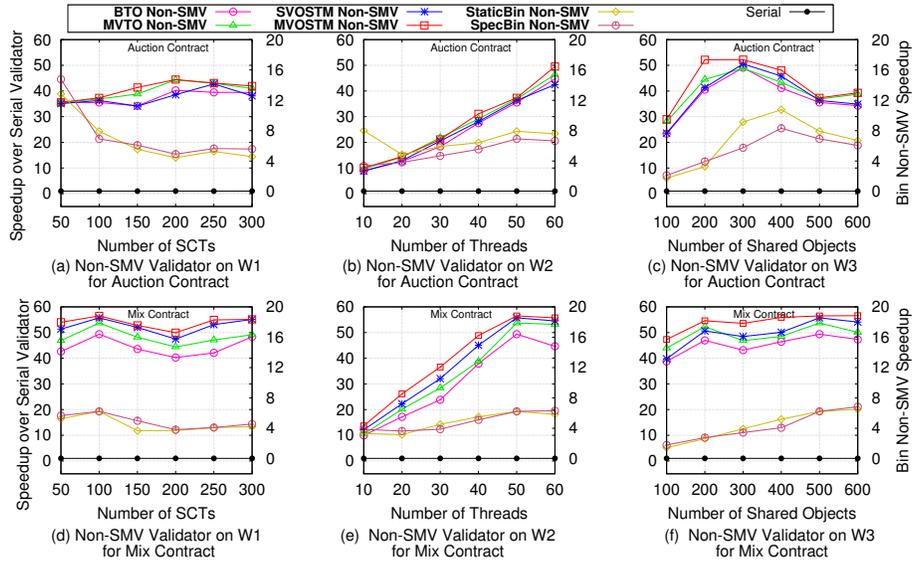


Fig. 24: Multi-threaded NonSMV Validator Speedup Over Serial Validator for Auction and Mix Contract

Performance Analysis of Fork-join SMV Validator: Fig. 25 and Fig. 26 show the performance of the fork-join validator [7,9]. Here we can observe that the average speedup achieved by the fork-join validator is very less compared to other SMV. The reason for low speedups by multi-threaded fork-join validators is possibly due to the working of the master thread, which becomes slow to allocate the SCTs to the slave threads and hence becomes the bottleneck.

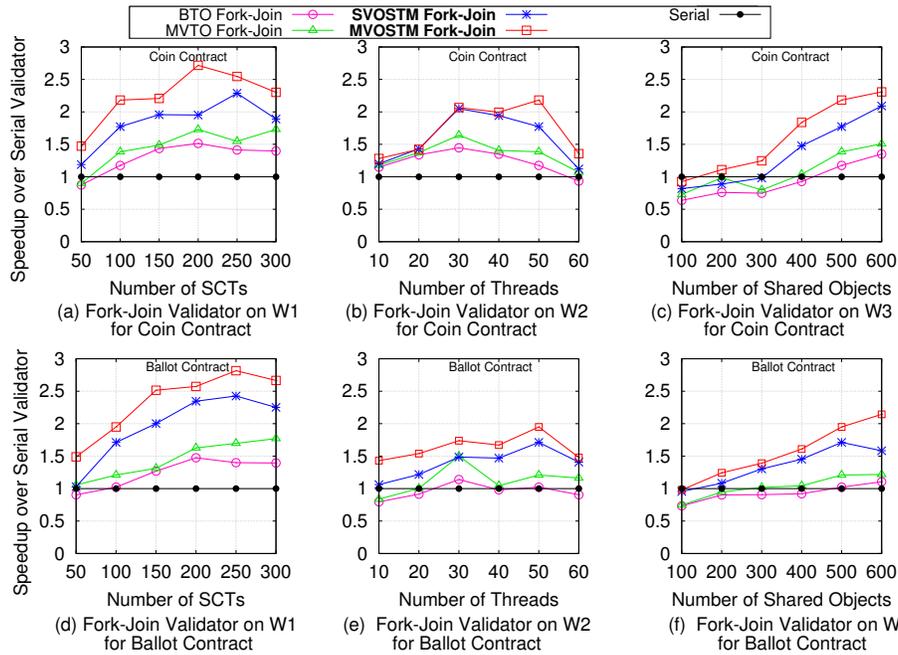


Fig. 25: Multi-threaded Fork-join Validator Speedup over Serial Validator for Coin and Ballot Contract

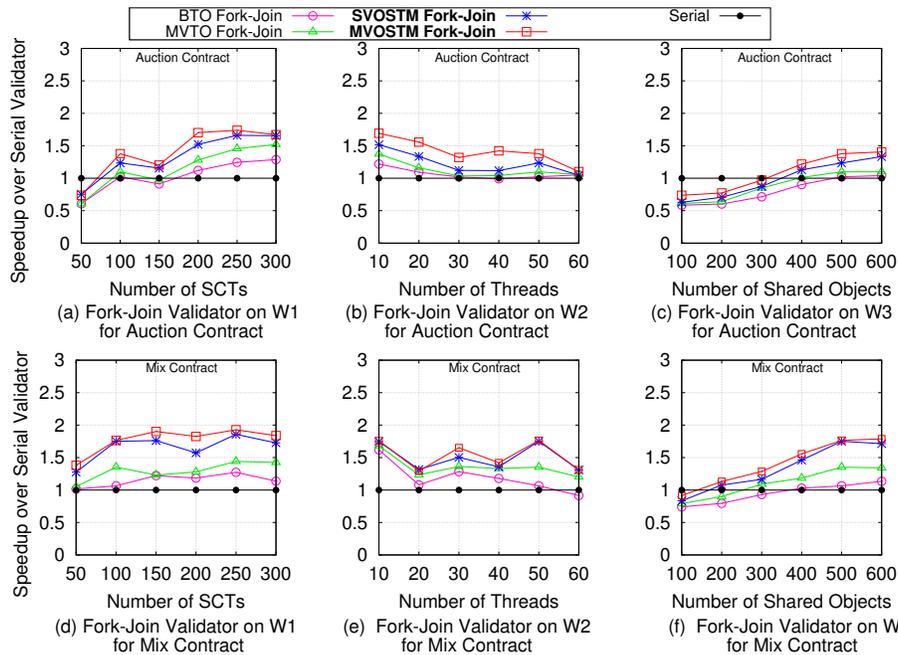


Fig. 26: Multi-threaded Fork-join Validator Speedup over Serial Validator for Auction and Mix Contract

Time Taken by Multi-threaded Miner and SMV on Workload-1 Benchmark Contracts: For the better clarity, we present the actual time taken by the miner and validators on W1. Table 4 to Table 7 show the time taken by the miners for all the four benchmark contracts, while Table 8 to Table 11 show the time taken by the validators. The time shown in the table is in the microsecond (μs) and averaged over 26 runs where the first run is considered as warm-up run and discarded.

Table 4: Multi-threaded v/s Serial Miner Time on W1 for Coin Contract (in μs)

# SCTs	Serial	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner	StaticBin Miner	SpecBin Miner
50	150.65	68.1112	50.3176	22.8232	14.9664	86.1328	12.7848
100	272.71	146.647	123.096	44.5568	37.464	159.595	33.1864
150	379.18	262.93	233.871	76.3768	55.584	271.694	49.1736
200	487.52	352.554	297.997	166.834	97.5192	527.921	72.2712
250	587.215	450.446	390.727	208.166	122.653	724.494	91.472
300	696.445	534.891	444.716	261.277	173.087	982.792	150.039

Table 5: Multi-threaded v/s Serial Miner Time on W1 for Ballot Contract (in μs)

# SCTs	Serial	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner	StaticBin Miner	SpecBin Miner
50	159.68	118.534	105.431	61.324	44.068	90.9888	35.4624
100	270.72	228.384	200.039	95.8848	86.2352	189.968	98.7128
150	426.24	425.461	357.151	171.871	162.211	424.124	181.074
200	524.64	656.821	723.909	264.23	274.261	674.95	310.022
250	633.32	897.225	919.69	338.452	410.184	846.106	423.346
300	775.96	955.438	1033.51	428.401	519.42	990.503	584.227

Table 6: Multi-threaded v/s Serial Miner Time on W1 for Auction Contract (in μs)

# SCTs	Serial	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner	StaticBin Miner	SpecBin Miner
50	106.8	18.0744	15.5328	14.3912	12.9552	45.8104	22.0304
100	239.04	86.7432	70.0488	45.6224	42.373	113.296	88.044
150	341.28	142.105	135.964	109.977	93.825	218.606	170.866
200	441.04	217.049	191.782	177.425	145.63	318.754	238.448
250	534.88	315.15	269.503	242.992	227.251	486.099	343.722
300	636.24	593.994	541.058	381.154	370.016	756.739	479.808

Table 7: Multi-threaded v/s Serial Miner Time on W1 for Mix Contract (in μs)

# SCTs	Serial	BTO Miner	MVTO Miner	SVOSTM Miner	MVOSTM Miner	StaticBin Miner	SpecBin Miner
50	101.96	44.8776	31.352	21.5408	20.0272	69.6816	19.3464
100	192.2	92.4168	66.972	44.2504	38.2416	140.606	52.9
150	223.08	182.382	155.381	66.3584	56.3176	240.282	70.8464
200	318.04	286.35	221.89	94.5632	82.5976	330.153	97.808
250	421.32	418.263	319.533	141.498	123.091	421.934	172.095
300	515.56	505.855	477.872	177.78	152.14	615.446	212.537

Table 8: SMV v/s Serial Validator Time on W1 for Coin Contract (in μs)

# SCTs	Serial	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	StaticBin SMV	SpecBin SMV
50	141.63	4.9848	4.7008	4.5784	4.6784	22.4432	21.5008
100	263.4	8.936	8.1272	7.2896	6.8432	47.392	26.2848
150	359.83	12.2552	11.8888	10.7256	9.6768	74.6168	57.9472
200	438.83	14.7144	14.1384	12.6072	11.9136	83.0256	71.7624
250	562.24	19.4272	18.6376	16.6352	16.1696	112.474	78.2856
300	664.305	23.658	22.439	22.3	20.0271	145.223	127.9989

Table 9: SMV v/s Serial Validator Time on W1 for Ballot Contract (in μs)

# SCTs	Serial	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	StaticBin SMV	SpecBin SMV
50	156.24	5.2896	5.0248	4.2376	4.0416	26.564	30.776
100	289.8	10.484	9.8752	7.5848	6.3024	68.3032	63.1488
150	425.2	13.4	12.792	9.7368	9.62	112.822	120.214
200	516.84	16.2848	15.3904	13.1784	12.4192	155.313	147.697
250	627.2	21.5944	19.6976	16.4096	15.3408	254.764	232.866
300	757.8	25.1328	23.8872	19.332	19.0984	293.702	261.422

Table 10: SMV v/s Serial Validator Time on W1 for Auction Contract (in μs)

# SCTs	Serial	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	StaticBin SMV	SpecBin SMV
50	103.4	3.2096	3.112	3.1424	3.1224	10.4136	8.6112
100	190.08	6.1088	5.2912	5.5608	5.2752	33.0736	30.668
150	290.6	9.916	8.0408	8.4984	7.9392	55.9136	48.576
200	406.48	12.4536	11.0552	11.324	10.8424	115.354	98.404
250	531.8	15.9936	14.2256	15.4752	13.8392	150.586	94.8384
300	606.4	19.048	16.0512	17.1448	15.1544	168.833	118.31

Table 11: SMV v/s Serial Validator Time on W1 for Mix Contract (in μs)

# SCTs	Serial	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	StaticBin SMV	SpecBin SMV
50	2.1936	2.0072	1.8232	1.7088	17.4024	16.3712	8.6112
100	4.1016	4.088	3.6	3.4512	31.7432	31.042	30.668
150	5.6592	4.812	4.7304	4.4384	58.816	42.975	48.576
200	7.3952	6.7504	6.224	6.0672	77.756	75.0021	98.404
250	9.4328	8.6696	8.0208	7.4904	94.9208	93.9526	94.8384
300	11.6016	10.5352	9.3392	8.9192	116.43	107.08	118.31