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DiPETrans: A framework for distributed parallel execution of transactions of blocks in blockchains

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Summary

Contemporary blockchain such as Bitcoin and Ethereum execute transactions serially by miners and validators and determine the Proof-of-Work (PoW). Such serial execution is unable to exploit modern multi-core resources efficiently, hence limiting the system throughput and increasing the transaction acceptance latency. The objective of this work is to increase the transaction throughput by introducing parallel transaction execution using a static analysis over the transaction dependencies. We propose the *DiPETrans* framework for distributed execution of transactions in a block. Here, peers in the blockchain network form a community of trusted nodes to execute the transactions and find the PoW in-parallel, using a leader–follower approach. During mining, the leader statically analyzes the transactions, creates different groups (shards) of independent transactions, and distributes them to followers to execute concurrently. After execution, the community's compute power is utilized to solve the PoW concurrently. When a block is successfully created, the leader broadcasts the proposed block to other peers in the network for validation. On receiving a block, the validators re-execute the block transactions and accept the block if they reach the same state as shared by the miner. Validation can also be done in parallel, following the same leader–follower approach as mining. We report experiments using over 5 million real transactions from the Ethereum blockchain and execute them using our *DiPETrans* framework to empirically validate the benefits of our techniques over a traditional sequential execution. We achieve a maximum speedup of 2.2× and 2.0× and an average speedup of 1.6× and 1.5× for the miner and the validator, respectively, with 100–500 transactions per block when using 6 machines in the community. Further, we achieve a peak of 5× end-to-end block creation speedup using a parallel miner over a serial miner.

KEYWORDS
blockchain, mining pools, parallel execution, smart contracts, static analysis

1 | INTRODUCTION

A blockchain is a distributed decentralized database that is a secure, tamper-proof, publicly accessible collection of the records organized as a chain of the *blocks*.[1,2] It maintains a distributed global state of the transactions in the absence of a trusted central authority. Due to its usefulness, it has gained widespread interest both in industry and academia.

All authors contributed equally to this work.

A blockchain consists of *nodes* or *peers* maintained in a peer-to-peer (P2P) manner. A node in the network may serve as a miner and/or as a validator. A *miner m* proposes a block to add to the blockchain, and hence is also referred to as a block producer in literature. A *block* generated by the miner consists of *transactions* typically encoding some business logic. Node *m* then solves a Proof-of-Work (PoW) to delay-wait the network and then broadcasts the block through the P2P network. The rest of the peers in the network, on receiving the block, validate the transactions in that block and the solution to the PoW. Hence, they are called as *validators*. *Clients*, also known as users, external to the system use the blockchain services by sending transactions to the network peers. On receiving a sufficient number of transactions from clients, a node takes the role of a miner to form a block. It then follows the mining and validation process to append the block to the blockchain. A block in a typical blockchain such as Ethereum[3] consists of a set of transactions, its timestamp, block id, nonce, coin base address (miner address), the hash of the previous block in the chain, the current block's hash, and so forth. The block is added to the blockchain through consensus between the peers validating the block. Usually, the entire copy of the blockchain is stored on all the nodes.

Bitcoin,[1] the first blockchain system proposed by Satoshi Nakamoto, is the most popular blockchain to date. It is a cryptocurrency system that is highly secure where users need not trust others. Further, there is no central controlling agency, like the current day banking system. Ethereum[3] is another popular blockchain that provides complex services in addition to cryptocurrencies such as user-defined scripts, called *smart contracts*. Such smart contracts are written in Turing complete language Solidity.[4] A smart contract is like an object in the object-oriented programming language, which consists of methods and data (state). They can be used to automatically define and enforce terms and conditions in the contract without the intervention of a trusted third party. A client's request to execute a contract's methods, also called a transaction, consists of the miner and validator nodes, invoking a series of these methods and their input parameters. Such contracts can be simple cryptocurrency exchanges between wallets or more complex logic such as Ballot and Simple Auction.[4]

Drawback with existing systems: Miners and validators in current blockchain systems execute the transactions serially. Further, finding the PoW, a computationally intensive brute-force process to create a new block. Miners compete to verify transactions and solve the PoW to create a block. Dickerson et al.[2] observe that the transactions are executed serially in two different contexts. First, executed serially by the miner while creating a block. Later, validators re-executes the transactions serially to validate the block. Typically, miners execute hundreds of transactions, and validators cumulatively execute millions of transactions serially for each new block. The serial execution of the transaction leads to poor throughput and is inefficient in the current era of distributed and multi-core systems. The high transaction fee, poor throughput (transactions/s), high block acceptance latency, and limited computation capacities prevent widespread adoption of blockchain.[5] Hence adding parallelism to the blockchain can improve efficiency and achieve higher throughput.

Solution approach: There are several solutions proposed and used in Bitcoin and Ethereum to mitigate these issues. One such solution is that several resource constraint miners form a *mining pool* or *community* to solve the PoW. After block acceptance, they share the incentive among them.[6-8]

Other solutions[2,9,10] suggest concurrent execution of the transactions at runtime in two stages: first while proposing the block, and second while validating the block. This helps in achieving better performance while creating the block and when validating, hence increasing the chance of a miner to receive their fees. However, it is not straightforward; it requires a proper strategy to avoid a valid block being rejected due to false block rejection (FBR) error[9] and to overcome malicious miners. Some of these use runtime techniques based on software transactional memory (STM) to execute transactions concurrently. A miner concurrently executes the block transactions and constructs the block graph alongside. The graph records dependencies between the transactions where vertices are the transactions and edges between them indicate a dependency. In the end, the miner adds the block graph to the block to help the validator execute these transactions concurrently and avoid FBR error.[9]

In contrast to those approaches, we propose to use a cluster of machines that form a community to execute or validate the transactions in a distributed manner based on a static analysis of the transactions. This improves the performance of both block mining and validation. The community has a *leader* machine and a set of *follower* machines. The leader is part of the blockchain while the follower nodes are at the disposal of the leader and are not part of the blockchain. The followers being at the disposal of the leader, form a trusted community with the leader, for example, they belong to the same organization.

The leader performs static analysis of the transactions in a block to identify dependencies and shards them into independent transactions, which are each executed in a distributed manner by the followers concurrently (see Figure 2). The miners and validators can each perform this static analysis for parallel execution. This avoids encoding the block dependency graph within the block, while also preventing FBR errors. When mining, the solution space for the PoW is also partitioned and solved in parallel by the followers. We implement and empirically validate the benefits of our approach within the Ethereum blockchain.[3] However, the proposed approach is generic and can be integrated into any other permissionless and permissioned (by excluding PoW computation of current approach) blockchain platform that follows an order-execute transaction execution model.[11] This implies *DiPETrans* can be integrated with any other consensus-based (such as PBFT) order-execute blockchain platform. To our knowledge, this is the first work that uses static analysis to identify block transactions that can be executed in parallel and combines them with the benefits of sharding and mining pools.

The *key contributions* of this article are as follows:

- We propose a *DiPETrans: Distributed parallel execution of transactions of blocks in blockchain* framework in Section 2 for parallel execution of the transactions at miners and validators, based on transaction shards identified using static analysis.
- We implement this technique using a distributed leader–follower approach within a mining community of servers, where the leader shards the transactions in the block and the followers concurrently execute (mining) or verify (validation) them. When mining, the PoW is also partitioned and solved in parallel by the members of the community.
- We report experiments in Section 3 using over 5 million real transactions from the Ethereum blockchain and execute them using *DiPETrans* to empirically validate the benefits of our techniques over traditional sequential execution. We achieve a maximum speedup of 2.2× and 2.0× and an average speedup of 1.64× and 1.52× for the parallel miner and parallel validator, respectively, with 100–500 transactions per block. Further, we achieve a maximum of 5× end-to-end block creation speedup using the parallel miner over a serial one, when using 6 machines in the community, including the leader.

We present related work in Section 4 and conclude with some future research directions in Section 5.

2 | PROPOSED FRAMEWORK

This section presents the proposed *DiPETrans* framework. We first provide an overview of the architecture that describes the functionalities of the miner and the validator. Following that, the leader–follower approach of a mining community is illustrated. Finally, the algorithms for static analysis of transactions and distributed mining are explained.

2.1 | DiPETrans architecture

Figure 1 shows the architecture of the *DiPETrans* framework. It shows two mining communities, one acting as a miner node and the other as a validator node in the blockchain. Each community internally has multiple computing servers that use their distributed compute power collaboratively to execute transactions and solve the PoW in parallel for a block. The resources can all be owned by the same user, or they may participate in parallel mining and get a part of the incentive fee based on pre-agreed conditions.

One of the community workers is identified as the *Leader*, while the others are *Followers*. The *Leader* represents the community and appears as a single peer in the blockchain network for all operations. Thus each peer of the blockchain in our architecture is the *Leader* of its respective community.

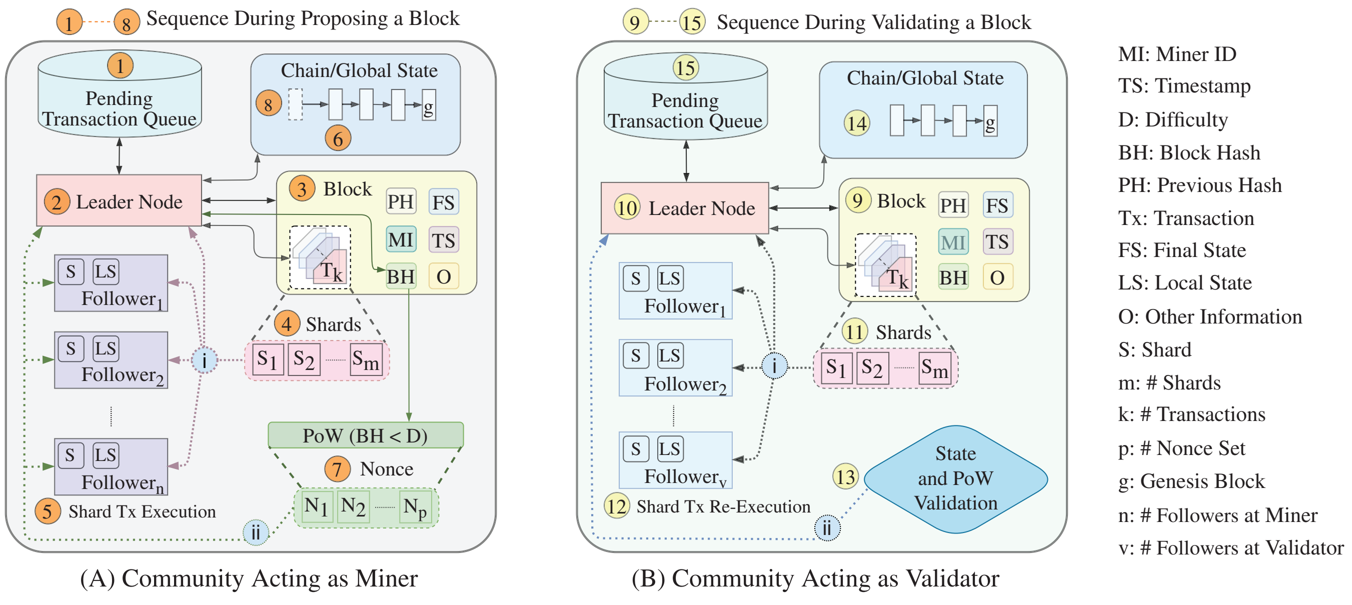


FIGURE 1 Overview of the DiPETrans architecture

When the user submits transaction request to one of the peers in the blockchain, the transaction is broadcast to every peer, including the *Leader* of each community. The broadcasted transaction is then placed in the pending transaction queue of the respective peers (Figure 1A①). Then all the miner peers in the blockchain compete to form the next block from these transactions.

2.1.1 | Community acting as miner

The leader node is responsible for coordinating the overall functionality of the community (Figure 1A②). It can be selected based on a leader election algorithm or some other approach. We assume that there are no server failures within the community. When the community acts as a miner to create new blocks, there are two phases: one is transaction execution (Figure 1Aⓘ, and the other is solving the PoW (Figure 1Aⓘⓘ). Both of these are parallelized; however, phase 2 may not be needed for permissioned blockchains.

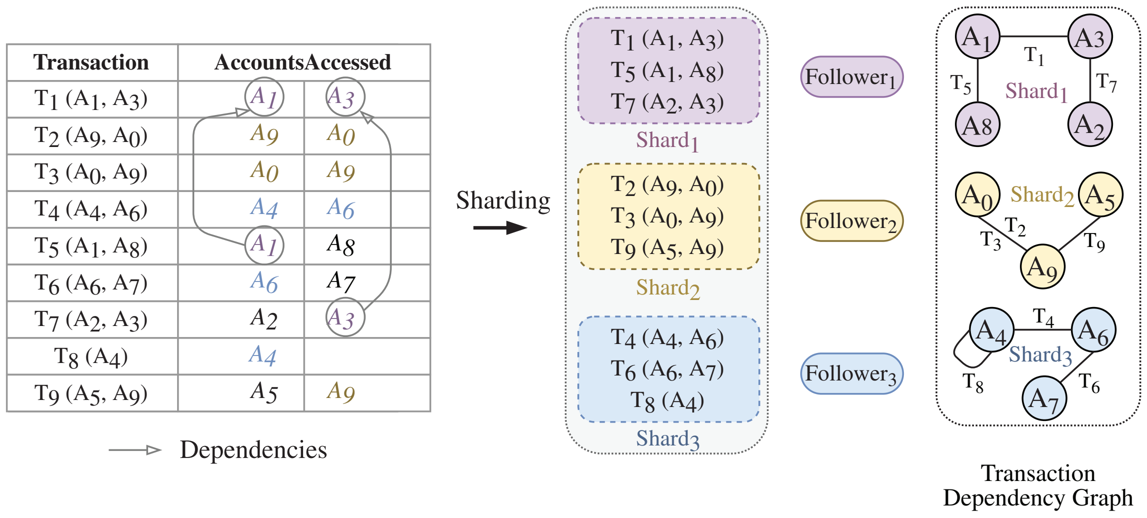
In the first phase, the leader selects the transactions from the pending transaction queue of the community (①) to construct a block (③). Then, it identifies the independent transactions by performing a static analysis of the transactions (discussed later in Algorithm 1). It groups dependent transactions into a single shard and independent ones across different shards (④). The leader then sends the shards to the followers, along with the current state of the accounts (stateful variables) accessed by those transactions (⑤, ⑥).

On receiving a shard from the leader, the follower (worker) executes the transactions present in its shard serially (⑤), computes the new state for the accounts locally, and sends the results back to the leader. While transactions across shards are independent, those within a shard may have dependencies (Figure 2), and hence are executed sequentially. To improve the throughput further, one can perform concurrent execution of transactions within a shard based on STM to leverage multi-processing on a single device (follower).[2,9,10] This is left as a future extension. Once all followers complete the execution of the shards assigned to them, the leader computes the block's final state from the local states returned by the followers.

In the PoW phase of the miner (⑦, ⓘⓘ), the leader sends the block header and transactions, and different nonce ranges to the followers. Each partition forms a solution space that a follower examines to find the block hash that is smaller than the target hash. This is an iterative brute-force approach that is computationally intensive. When a follower finds the correct hash, it informs the leader. The leader then notifies the remaining workers to terminate their computation. The leader proposes the block with the executed transactions and the PoW, updates its local chain (⑧), and broadcasts it to all peers in the blockchain network for validation. A successful validation by a majority of peers and the addition of the block to the consensus blockchain will result in the mining community receiving the incentive fee for that block.

2.1.2 | Community acting as validator

When the community acts as a validator, its first phase is similar to the miner, while in its second phase, it just validates the PoW done by the miner.



Transaction	**AccountsAccessed**	
T_1 (A_1, A_3)	A_1	A_3
T_2 (A_9, A_0)	A_9	A_0
T_3 (A_0, A_9)	A_0	A_9
T_4 (A_4, A_6)	A_4	A_6
T_5 (A_1, A_8)	A_1	A_8
T_6 (A_6, A_7)	A_6	A_7
T_7 (A_2, A_3)	A_2	A_3
T_8 (A_4)	A_4	
T_9 (A_5, A_9)	A_5	A_9

FIGURE 2 Sharding of transactions in a block using static graph analysis

After receiving a block from a miner (Figure 1B⑨), the remaining peers of the blockchain network serve as its validators. They validate the block by re-executing the transactions present in the block and check if the PoW hash matches. Verifying the PoW hash is computationally cheap. The transaction re-execution is identical to the first phase of mining (Figure 1B⑨–⑮,$\textcircled{i}$), and use the same Algorithm 1 for static analysis of the dependencies themselves. We will call such validator as *Default Validator* (we will explain other validators later). They then verify if the block contains the correct PoW solution (Figure 1B$\textcircled{ii}$), and validate the final state computed by them based on their local chain with the final state supplied by the miner in the block (Figure 1B⑬). If the final state computed does not match with the final state in the block stored by the miner, then the block is rejected. The miner does not get any incentive in this case.

Alternatively, a validator can also execute the transactions serially if they are not part of any community, that is, *stand-alone validators*. Yet another approach for the validator is that miners encode hints on the transaction dependency as part of the block,[2,9,10] which allows the validators to avoid performing the static analysis again. Specifically, the miner includes the shard ID for each transaction in the *other* field of the block (Figure 1$\boxed{O}$), and this can directly be used by the validator to shard the transactions for parallel validation. We refer to these as *Sharing Validators*. But, the problem here is that the miners can encode an invalid transaction dependency information that can cause the validation to be incorrect.[10] This problem does not arise in our default validator since the static analysis is done independently by them. In our experiments, we compare the performance benefit of these approaches.

2.1.3 | Sharding of the block transactions

Sharding is the process of identifying and grouping the dependent transactions in a block, with one shard created per group. This is illustrated in Figure 2, which lists a sequential list of transactions that are received at a node. Transaction T_1 accesses the account (stateful variable) A_1 and A_3, T_5 accesses A_1 and A_8, while T_7 accesses A_2 and A_3. Since T_1, T_5, and T_7 are accessing common accounts, they are dependent on each other and grouped into the same shard, $Shard_1$. Similarly, transactions T_2, T_3, and T_9 are grouped into $Shard_2$, while T_4, T_6, and T_8 are grouped into $Shard_3$. Transactions in each shard are independent from those in other shards, and each shard can be executed in parallel by different followers of the community. However, transactions within a shard must be executed in the original order in which they arrived.

Algorithm 1. `Analyze()`

```
Data: txnsList
Result: sendTxnsMap
Procedure Analyze(txnsList):
    // Prepare AdjacencyMap, ConflictMap, AddressList to find WCC
    Map<address, List<txID>> conflictMap;
    Set<address> addressSet;
    Map<address,address> adjacencyMap;
    for tx ∈ txnsList do
        conflictMap[tx.from].put(tx.txID);
        conflictMap[tx.to].put(tx.txID);
        addressSet.put(tx.from);
        addressSet.put(tx.to);
        adjacencyMap[tx.from].put(tx.to);
        adjacencyMap[tx.to].put(tx.from);
    end
    Map<shardID, Set<txID>> shardsMap;
    // Call to WCC till all addresses are visited
    shardsMap = WCC (addressSet, conflictMap);
    Map<followerID, List<Transaction>> sendTxnsMap;
    // Equally load balance the shards for followers
    sendTxnsMap = LoadBalance (shardsMap, followerList, txnsList);
return sendTxnsMap
```

We model the problem of finding the shards using static analysis (Algorithm 1) as a graph problem. Specifically, each *account* serves as a *vertex* in the *transaction dependency graph*, identified by its *address*. We introduce an *undirected edge* when a transaction access two accounts, identified

Algorithm 2. `LoadBalance`()

```
Data: shardsMap, followerList, txnsList
Result: sendTxnsMap
Procedure LoadBalance (shardsMap, followerList, txnsList):
    Map<int, List<Transaction>> sendTxnsMap ;
    // Sort the shards in decreasing order of transaction count
    shardMap = sorted(shardMap, reverse = True)
    for ccID ∈ shardMap do
        // Find the followerID which has least number of transactions and assign them the shard
           transactions
        Map<int, List<Transaction>>::iterator $it_1$, $it_2$;
        for $it_1$ ∈ sendTxnsMap do
            for ($it_2$ ∈ sendTxnsMap) do
                if $it_1 \rightarrow second.size() > it_2 \rightarrow second.size()$ then
                    // Follower id with least number of transactions
                    $id = it_2 \rightarrow first - 1$;
                    // Assignment of shard transactions
                    for txid ∈ shardMap[ccID] do
                        sendTxnsMap[followerList[id].followerID].add(txnsList[txid]);
                    end
                end
            end
        end
    end
return sendTxnsMap
```

by its *transaction ID*. A single transaction accessing n addresses will introduce $\frac{n(n-1)}{2}$ edges, forming a clique among them. Next, we find the *Weakly Connected Component (WCC)* in this dependency graph. Each component forms a single shard and contains the edges (transactions) that are part of that component. The transactions within a single shard are present in their sequential order of arrival. Transactions that are not dependent on any other transaction are not present in this graph and are placed in singleton shards. This is illustrated in Figure 2.

The number of shards created may exceed the number of followers. In this case, we attempt to load-balance the number of transactions per follower. To achieve this, the leader sorts the shards in decreasing order of transaction count and assigns each shard to the follower with the least current load of transactions using Algorithm 2. As long as the number of shards is many and we do not have skewed shards with many transactions that can overload a single worker by itself, this bin-packing algorithm achieves load balancing.

For example, in experiments for a block with 100 transactions, there are ≈39 shards and ≈6 transactions in the largest shard on an average. Moreover, load balancing of the shards among the 5 followers results in each follower being assigned ≈25 transactions (refer Figures 10 and 11). Here, we assume that all transactions take the same execution time, which may not be true in practice since smart contract function calls may vary in latency, and be costlier than non-smart contract (monetary) transactions as we can observe that in the experiments section. However, if we have an estimate of the transaction duration, existing scheduling algorithms can be easily adapted to these as well. Similarly, heterogeneity in the computational capability of followers can be handled as well.

2.1.4 | Time complexity analysis

The running time complexity for the DiPETrans approach depends on the number of shards, the number of transactions assigned to each shard, and the shards assigned to each follower. This has three components: the initial overheads to partition and assign shards to followers, the time to execute transactions concurrently across followers, and the time for parallel mining of the POW.

Let an input block have n transactions. The `Analyze` function takes $\mathcal{O}(n)$ to build the transaction graph with n edges and between 2 to 2n vertices. So finding the dependencies using WCC on this graph also takes $\mathcal{O}(n)$ to identify the shards. This gives a time complexity of $\mathcal{O}(n)$ for the `Analyze` phase. Say we have m shards and f follower nodes in the community. The `LoadBalance`function takes $\mathcal{O}(m \cdot \log(m))$ to initially sort the shards. Then, for faster execution, we can use a priority queue to maintain the number of shards and transactions assigned to each follower. In this case, we get a time complexity of $\mathcal{O}(m \cdot \log(f))$ to assign the shards to followers. This comes from the observation that we are inserting f followers m times with each insert taking $log(f)$ time. Combining the time taken by both the routines, gives a time complexity of $\mathcal{O}(m \cdot (\log(m) + \log(f)))$ for the `LoadBalance` phase. So the initial overheads have an overall time complexity of $\mathcal{O}(n + m \cdot (\log(m) + \log(f)))$. Usually, with $m > f$, this reduces to an expected complexity of $\mathcal{O}(n + m \cdot \log(m))$.

The time to complete the transaction execution is limited by the follower with the most number of transactions, assuming all transactions take about the same amount of time, t_x. So, in the best case, the peak number of transactions assigned to a follower ranges from $\frac{n}{f}$, with perfect load balancing to n; in the worst case, there is only one shard with all the transactions. So the worst-case time complexity for transaction execution is $\mathcal{O}(n \cdot t_x)$ and a best-case time complexity of $\Omega(\frac{n}{f} \cdot t_x)$. Lastly, the PoW can be mined by the followers with perfect parallelism. So if t_p is the time to find the PoW serially, the time complexity for finding it in parallel is a tight bound $\Theta(\frac{t_p}{f})$.

2.2 | Sequence of operations

Figure 3 shows the sequence diagram for processing a block by a miner and a validator community in *DiPETrans*. There are four roles as *LeaderMiner*, *FollowerMiner*, *LeaderValidator*, and *FollowerValidator*. At the top of Figure 3, we see the *LeaderMiner* starts the block execution by creating a block from the transaction queue. The created block consists of a set of transactions (b), including block specific information such as timestamp, miner details, nonce, hash of the previous block, final state, and so forth. The transactions of the block are formed into a dependency graph for static analysis. The WCC algorithm used to identify disjoint sets of transactions that form shards (c). Load balancing and mapping of shards to followers are done as well. The *LeaderMiner* then sends the shards to the follower devices in parallel (d), and these are executed locally on each follower (e). After successfully completing the transactions, each *FollowerMiner* sends the updated account states back to the *LeaderMiner* (f). The *LeaderMiner* updates its global account state based on the responses received from all the *FollowerMiners* (g).

Once all *FollowerMiner* complete executing their assigned shard(s), the *LeaderMiner* switches to the PoW phase. It assigns followers the task of finding the PoW for different ranges of the nonce concurrently (h). The *FollowerMiner* searches the range to solve the PoW (i) and returns a response either when the PoW is solved, or their nonce range has been completely searched (j). A successful detection of a solution by one follower causes the leader to terminate the PoW search on other followers. Finally, the *LeaderMiner* broadcasts the block containing the transactions, the updated account states, the PoW, and optionally the mapping from shards to transactions (required for *Sharing Validators*) to the peers in the blockchain network for validation (k).

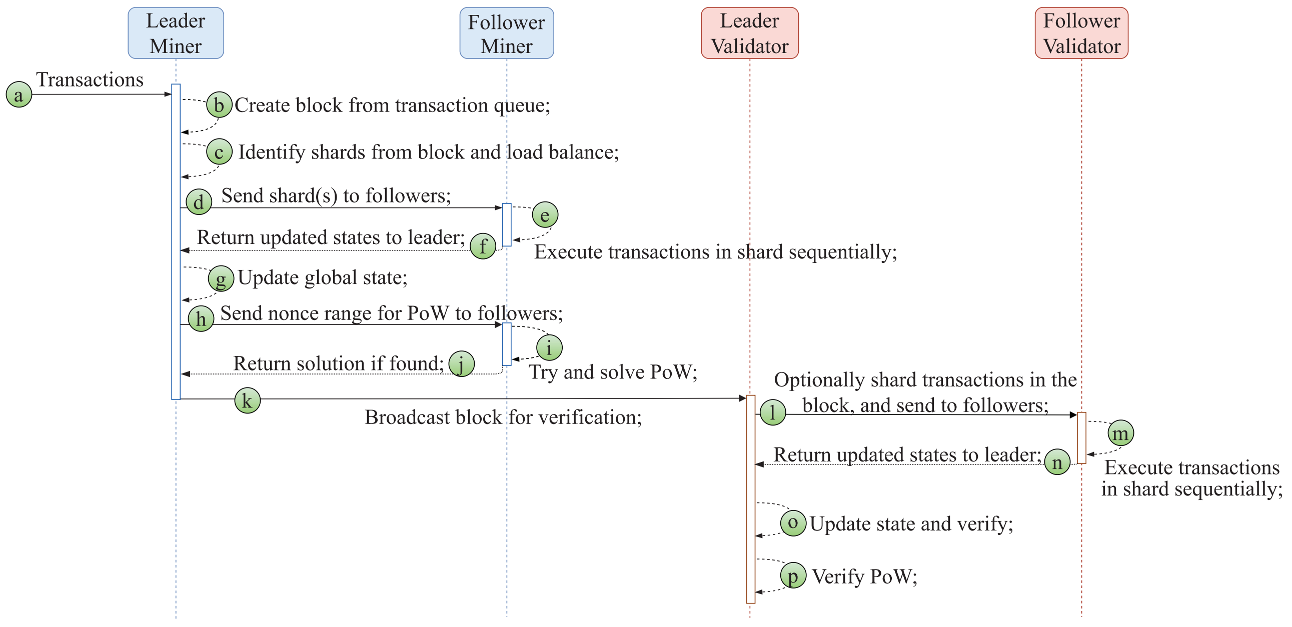

Leader Miner
Follower Miner
Leader Validator
Follower Validator
a Transactions
b Create block from transaction queue;
c Identify shards from block and load balance;
d Send shard(s) to followers;
e
Return updated states to leader; f
Execute transactions in shard sequentially;
g Update global state;
h Send nonce range for PoW to followers;
i
Return solution if found; j
Try and solve PoW;
k
Broadcast block for verification;
Optionally shard transactions in the block, and send to followers;
l
m
Return updated states to leader; n
Execute transactions in shard sequentially;
o Update state and verify;
p Verify PoW;

FIGURE 3 Sequence diagram of operations during mining and validation

At the lower part of Figure 3, we see a *LeaderValidator* receives a block to verify. It needs to re-execute the block transactions and match the resulting account states with those present in the block. For this *LeaderValidator*, either use the shard information present in the block (*Sharing Validator*) or, if not present, determine it using the same dependency graph approach as the *LeaderMiner* ⓒ. *LeaderValidator* uses the *Sharing Validator* approach if it trusts the *LeaderMiner*. Then *LeaderValidator* assigns the shards to the *FollowerValidators* ⓛ. After successfully executing the transactions assigned by *LeaderValidator* ⓜ, each *FollowerValidator* returns the account states back to the *LeaderValidator* ⓝ. The responses are verified by the *LeaderValidator* with the states present in the block ⓞ. The *LeaderValidator* also confirms that miner has correctly found the PoW ⓟ. After both these checks succeed, the *LeaderValidator* accepts the block and propagates the message to reach the consensus.

2.3 | Community trust model

Trust is the probability with which an entity will perform a particular action, and how it in turn affects another entity's behavior.[12] In DiPETrans, the trust model among the peers follows existing blockchain networks, wherein *more than half* the nodes in the network are trusted and not malicious.[13] Depending on the blockchain, the nodes may be *permissioned* or *permissionless*—in the former, the identity of each node is known through authentication or other mechanisms. However, all nodes within each community, which act as a miner or as a validator, are permissioned. We assume implicit trust between all these nodes and no malicious or faulty behavior.

While we do not discuss the means to ensure this trust model, various security measures can be employed, such as authentication, authorization, access control, and so forth, to add and validate the identity of new nodes. Any faulty or malicious behavior of a node on the community can cause that community to behave as a malicious peer in the blockchain network, which as such is handled by the blockchain's validation requirements. As future work, we can consider scenarios where nodes in the community may be malicious and the (trusted) leader can identify such nodes based on the re-execution of a rejected block transactions and final state computation.

3 | EXPERIMENTS AND RESULTS

In this section, we first provide an overview of the *DiPETrans implementation*, followed by a description of the *transactions workload*, *experimental setup*, and *performance analysis* based on *execution time* and *speedup* achieved by our proposed approach over a serial version.

3.1 | Implementation

We modeled and implemented *DiPETrans* as a stand-alone permissioned blockchain framework (such as Quorum[14] while excluding PoW in a permissioned setting) that operates on Ethereum blockchain transactions. The leader and followers are designed as a set of micro-services that perform mining and validation operations. These include the new operations proposed in *DiPETrans*. Our implementation focuses on operations within the mining community rather than with the rest of the blockchain network. The leader serves as a node with the usual Ethereum functions. The implementation is in *C++* using the Apache thrift cross-platform micro-services library.

We made several simplifying assumptions to focus on our goal of concurrent executions of block transactions (in the permission or permissionless blockchain). As mentioned in Section 1, all nodes within a community (leader and followers) *trust* each other, for example, they belong to the same institute or organization or crypto exchange. However, this can be extended in the future to a trustless community using node profiling, which decreases the reputation of malicious nodes,[15] detects and removes them. The peers are assumed to be *reliable*. In the future, worker failures can be addressed by distributing the shards of a failed worker to others based on a work-stealing approach. Further, we assumed a *fixed community structure* where the leader knows all the followers when processing a block. The addition and removal of followers or even the leader are not considered here. These issues can partly be addressed using existing techniques[8] for both trusted and trustless communities.

3.2 | Transactions workload

Our experiments used real historical transactions from the Ethereum blockchain available from Google's Bigquery public data archive as on March 13, 2021.[16] The transactions used start from block number 4,370,000, which forms a hard fork when Ethereum changed the mining reward from

5 to 3 Ethers. We extracted ≈80k blocks containing 5,170,597 transactions. While the original transactions had 17 fields, we selected 6 fields of interest as part of our workload. These include the `from_address` of the sender, the `to_address` of the receiver, `value` transferred in *Wei* (the unit of Ethereum currency), `input`data sent along with the transaction, `receipt_contract_address` the contract address when it is created for the first time, and `block_number` where this transaction was present in.

There are two types of transactions we considered: *monetary transactions* and *smart contract transactions.*[17] In the former, also known as value transfer or non-contractual transaction, *coins* are transferred from one account to another account. This is a simple and low-latency operation. In a contractual transaction, one or more smart contract functions are invoked. We observed that there are 127 unique Solidity functions in 20k contracts, out of which we implemented the top 11 most frequently invoked ones (Table 2) that cover ≈80% of all contract transactions. These contract functions implemented in the Solidity language of Ethereum are re-implemented as C++ function calls. These can be invoked by the peers in our framework as part of their transaction execution.

Of the ≈5 million transactions present in the Ethereum blocks, we considered 193,959 smart contract transactions. We believe that over time, the wider use of smart contracts will ensure that they form a larger fraction than just monetary transactions. Contract transactions are also more compute-intensive to execute than monetary transactions. Thus they can benefit more from our distributed framework. Hence, we created workloads with different ratios between contract and monetary transactions: $\rho \in \left\{\frac{1}{1}; \frac{1}{2}; \frac{1}{4}; \frac{1}{8}; \frac{1}{16}\right\}$. Each block formed by miners has between 100 and 500 transactions in this ratio, depending on the workload used in an experiment. This workload used in our experiments is described in Table 1. Here, the block *data-1-2-300* means $\rho = \frac{1}{2}$ is the ratio of contractual to monetary transactions per block while 300 is the total number of transactions in this block.

TABLE 1 Summary of transactions in experiment workload

Block type	ρ	# Txns/block	# Blocks	∑# Contract txns	∑# Non-contract txns
data-1-1-100	$\frac{1}{1}$	100	3880	193,959	194,000
data-1-1-200		200	1940	193,959	194,000
data-1-1-300		300	1294	193,959	194,100
data-1-1-400		400	970	193,959	194,000
data-1-1-500		500	776	193,959	194,000
data-1-2-100	$\frac{1}{2}$	100	5705	193,959	376,530
data-1-2-200		200	2895	193,959	385,035
data-1-2-300		300	1940	193,959	388,000
data-1-2-400		400	1448	193,959	385,168
data-1-2-500		500	1162	193,959	386,946
data-1-4-100	$\frac{1}{4}$	100	9698	193,959	775,840
data-1-4-200		200	4849	193,959	775,840
data-1-4-300		300	3233	193,959	775,840
data-1-4-400		400	2425	193,959	776,000
data-1-4-500		500	1940	193,959	776,000
data-1-8-100	$\frac{1}{8}$	100	16, 164	193,959	1,422,432
data-1-8-200		200	8434	193,959	1,492,818
data-1-8-300		300	5705	193,959	1,517,530
data-1-8-400		400	4311	193,959	1,530,405
data-1-8-500		500	3464	193,959	1,538,016
data-1-16-100	$\frac{1}{16}$	100	32, 327	193,959	3,038,738
data-1-16-200		200	16, 164	193,959	3,038,832
data-1-16-300		300	10, 776	193,959	3,038,832
data-1-16-400		400	8082	193,959	3,038,832
data-1-16-500		500	6466	193,959	3,039,020

TABLE 2 Most frequent functions invoked by contract transactions

#	Function	Function hash	Parameter types	# Txns	%'ile
1	transfer	0xa9059cbb	address, uint256	56, 654	37.72
2	approve	0x095ea7b3	address, uint256	11, 799	45.58
3	vote	0x0121b93f	uint256	11, 509	53.24
4	submitTransaction	0xc6427474	address, uint256, bytes	8163	58.67
5	issue	0x867904b4	address, uint256	5723	62.49
6	__callback	0x38bbfa50	bytes32, string, bytes	5006	65.82
7	playerRollDice	0xdc6dd152	uint256	4997	69.15
8	multisend	0xad8733ca	address, address[], uint256[]	4822	72.36
9	SmartAirdrop	0xa8faf6f0	–	4467	75.33
10	PublicMine	0x87ccccb3	–	4157	78.10
11	setGenesisAddress	0x0d571742	address, uint256, bytes	3119	80.17

We define two transaction workloads with different mixes of these block types. In *Workload-1*, the number of transactions per block varies from 100 to 500, and within each, we include all available ratios of ρ, from $\frac{1}{1}$ to $\frac{1}{16}$, that is, all the blocks in Table 2 are used. In *Workload-2*, only blocks with 500 transactions are used, but with all available ratios ρ, that is, *data-1-1-500* to *data-1-16-500*.

3.3 | Experimental setup

We used a commodity cluster to run the leader and followers in the mining and validation communities for our *DiPETrans* blockchain network. Each node in the cluster has an 8-core AMD Opteron 3380 CPU with 32 GB RAM, running CentOS operating system and are connected using 1 Gbps Ethernet. A mining community has a leader running on one node and between one to five followers, each running on a separate node, depending on the experiment configuration. Similarly, a validation community has one leader and between one to five followers. They all run in a single-threaded mode for simplicity, though this can be extended to multi-threading with each thread serving as a follower.

3.4 | Performance analysis

For each workload, blocks are executed for a serial configuration and for a parallel configuration with 1–5 followers. The serial execution serves as the baseline for comparing the performance improvement of the parallel setup. Further, we executed these in different modes. One, the miner only executes the transaction and omits the PoW. Since parallelizing the PoW available in the existing literature (e.g., mining PoW available in the existing literature (e.g., mining pools),[6-8,18,19] this setup highlights the novel value of our static analysis technique for both mining and validation in the permission or permissionless blockchain. Also, we performed experiments with both variants of the validator: default and sharing. Two, the miner performs both transaction execution and PoW computation with concurrency benefits from both. These are described next.

3.4.1 | Transaction execution time

This section presents the results and analysis for executing transactions at the miner and verifying them at the validator. It omits the time to find the PoW at the miner and verifying it at the validator. The serial execution serves as a baseline.

Figures 4 and 6 show the *average execution time per block (in ms)* for Workload 1 and Workload 2, respectively, for the different modes of execution. For Workload 1, the number of transactions per block increases in the *X*-axis, while for Workload 2, the contract to monetary transaction ratio ρ varies. Subfigure A is for the miner, and subfigures B and C are for the default and sharing validators.

Figures 5 and 7 show the speedup of our parallel execution, relative to the serial execution.*

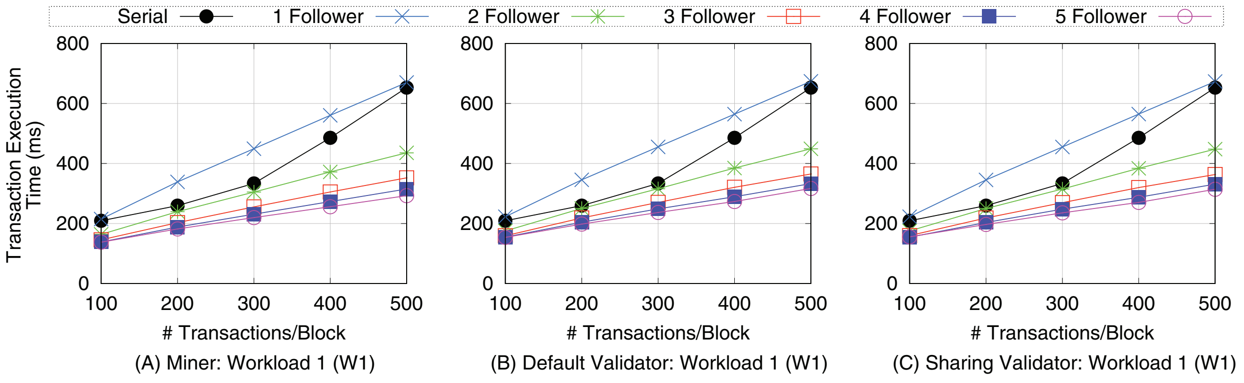


FIGURE 4 Workload-1: Average transaction execution time by miner (omitting time to find PoW) and validator

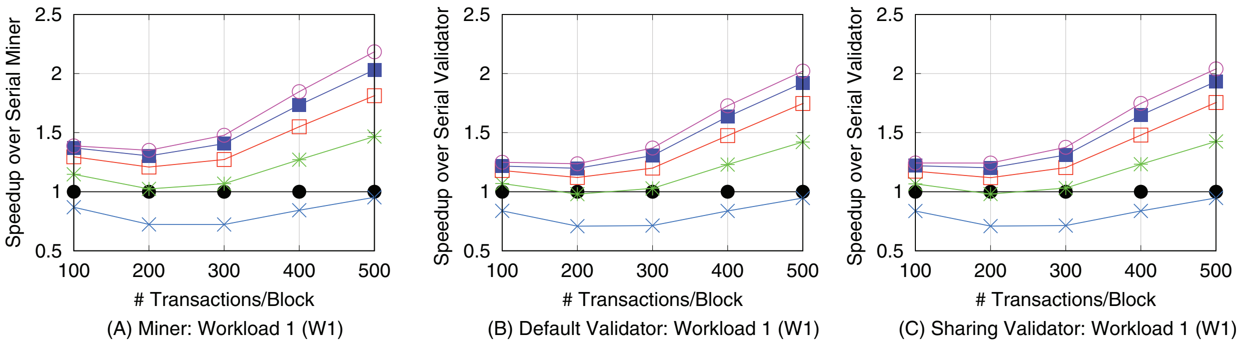


FIGURE 5 Workload-1: Average speedup by community miner and validator over serial miner and validator for transaction execution

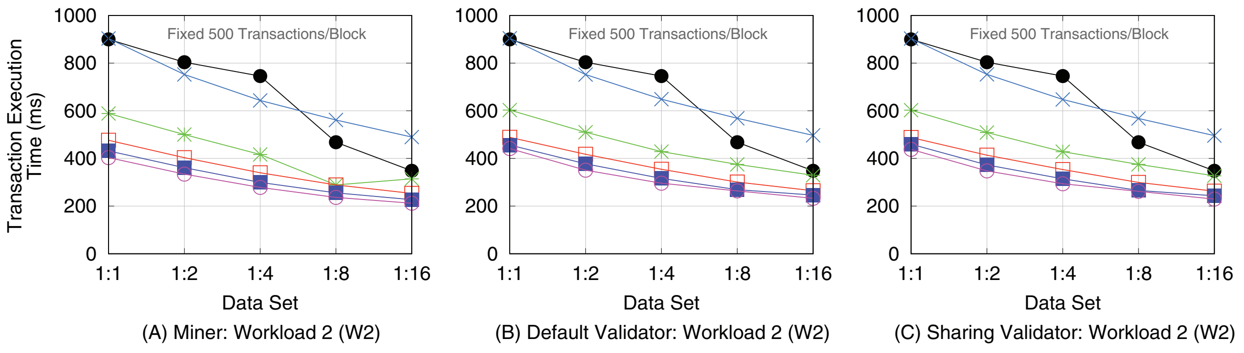


FIGURE 6 Workload-2: Average transaction execution time by miner (omitting time to find PoW) and validator

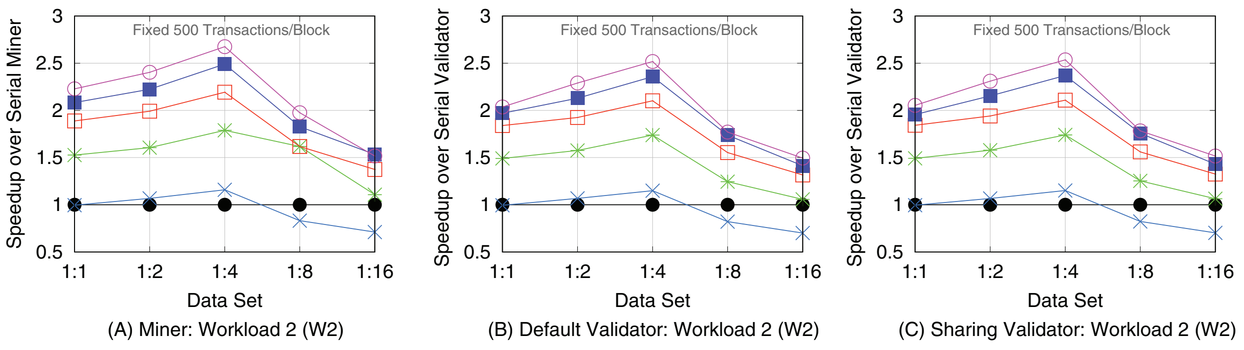


FIGURE 7 Workload-2: Average speedup by community miner and validator over serial miner and validator for transaction execution

Workload-1: As shown in Figure 4, the average execution time per block increases as the number of transactions in a block increases from 100 to 500. Each block size in this workload includes all values of ρ, the ratio. This growth is linear, except for the serial execution that shows an increase in the slope beyond 300 transactions per block.

We also see that the 1 follower configuration is performing worse than the serial execution due to the overhead of static analysis at the leader and communication between the leader and follower. However, other configurations with 2–5 followers offer faster execution times than serial execution.

Figure 4B,C shows the line plots for the average transactions execution time per block, taken by *Default Validator* and *Sharing Validator*, respectively. The only difference between these two validators is that *Default Validator* runs static analysis on the block transactions before execution, while *Sharing Validator* reuses the dependency graph encoded in the block. The results for both these validators are near-identical and also closely match the results for the miner. The former indicates that the transaction validation time dominates, and the overheads for static analysis are negligible. Further, since the miner in this experiment only executes transactions and not the PoW, it is understandable that the validators that use a similar transaction execution phase exhibit similar results.

When we examine the parallel speedup for this workload relative to the serial execution in Figure 5, we observed that the speedup increases with an increasing number of followers. As seen before, with 1 follower, the speedup is below 1× while with 5 followers, the peak speedup achieved is 2.18×. The speedup also improves as the number of transactions per block increases. This causes shards with a larger number of transactions to be created, and parallelization of the higher computational load amortizes the static analysis and the communication overheads. However, the speedup efficiency is sub-optimal at about 51% for 4 followers and 44% for 5 followers, with 500 transactions/blocks.

A similar trend is observed for the validators. We also noticed that the speedup curves for *Sharing Validator* and *Default Validator* are comparable. This means that the benefits of a *SharingValidator* are negligible as compared to the *DefaultValidator* due to the minimal time taken by the static analysis. Further, we observed that static analysis is not a bottleneck for the leader in this workload due to presence of only hundreds of transactions per block. So this leads us to conclude that *Default Validator* should suffice. Moreover it also avoids encoding the transaction dependency graph into the block as required by a *Sharing Validator*. The validators' average speedup is 1.25×, and their peak is 2.03× with 5 followers and 500 transactions per block.

Workload-2: In this workload, the transactions per block are fixed at 500 while we vary the ratio ρ. Figure 6 shows the average transaction execution time taken by the miner and the two types of validators in the Y-axis as the value of ρ increases along the X-axis. We observed that reducing the ratio of contract transactions relative to the non-contractual transactions reduces the average time taken to mine or validate a block. This can be explained by the higher computational complexity of the smart contracts that execute non-trivial external function calls as part of the transaction logic.

Unlike Workload 1, the 1 follower scenario is comparable to the serial setup rather than slower. Having more than 1 follower offers consistently better performance than serial. However, with the increase of non-contractual transactions in a block, the serial execution starts even to match the time taken by more followers. Here, given the short absolute execution time of about 400 ms per block for $\rho = \frac{1}{16}$ due to the simple non-contractual transactions, it is possible that the round trip communication time between the leader and the follower may start to have a tangible impact. In Figure 6C, we can observe that the time required to execute more transactions per block decreases as the number of contract transactions decreases. These trends are common to the miners and the two validators.

Interestingly, in Figure 7, the speedup curve shows improvement as the value of ρ increases until $\frac{1}{4}$ and drops after that. This indicates that the sweet-spot of parallel efficiency lies with this mix of the contract and non-contract transactions, offering a peak speedup of 2.7× with 5 followers and a favorable speedup efficiency of 73% with 3 followers.

3.4.2 | End-to-end mining time

Here we present the analysis for end-to-end block creation time by the miner, which includes the transaction execution time as well as the time to find the PoW.

Existing blockchain platforms such as Bitcoin, Ethereum maintain, and modulate a factor called *difficulty*[21] in the block creation (mining) process. These systems calibrate the difficulty using carefully designed difficulty algorithm to keep the mean end-to-end block creation time within limits like in Bitcoin which ensure that every two weeks, that is, after 2016 blocks the difficulty is calibrated to ensure that the inter-block addition time is ≈10 min.[21]

The difficulty is calibrated based on how much time it takes for mining. If it has taken more than 2 weeks, the difficulty is reduced otherwise it is increased. In addition to this, several other factors are also considered to change the difficulty. While in Ethereum blockchain, roughly tries to maintain the block production time to be around 10–19 s. So the difficulty is fixed accordingly. After every block creation, if mining time goes below 9 s, then *Geth*, a multipurpose command line tool that runs Ethereum full node, tries to increase the difficulty. In case when the block creation difference is more than 20 s, Geth tries to reduce the mining difficulty of the system. Solving PoW is an inherent brute-force task. Blockchain platforms calibrate the difficulty of solving it to ensure that the average block creation time remains within limits as hardware technology improves and the mix of transactions varies. For simplicity, in our experiments, we fixed the difficulty per block to be a static value.

Figure 8 shows the average execution time for each block on the *Y*-axis, which includes the transaction execution time and PoW time, as the number of transactions per block increases (Workload 1) or the value of ρ varies (Workload 2). In contrast to the earlier experiments, we can clearly see that the execution time has increased by orders of magnitude by introducing the PoW, ranging between 10 and 60 s per block for the serial execution. We also see an apparent linear growth in time as the transactions per block increases in Workload 1. When seen along with the speedup plots in Figure 9A, we observe a substantial improvement in the average block creation time as the number of followers increase. We have a speedup of 1.15× to 4.91× for 1–5 followers that remain stable as the block size increases, with a speedup efficiency of 57.5%–81.83%. Figure 8B for Workload 2, where the monetary transactions increases per block, the mining time sometimes increases and sometimes decreases. We achieve a maximum speedup of 1.17× to 4.82× for 1–5 followers, with a speedup efficiency of 58.5%–80.33% in Workload 2.

3.4.3 | Sharding analysis

Here in this section, we present the analysis for the number of shards per block, transactions in a shard, and the transactions allocated to a follower on both the workloads. In Workload 1, the number of transactions per block varies, while in Workload 2 ratio (ρ) of non-smart contract (monetary) transactions to smart contract transactions vary where transaction counts per block remained 500 for all the cases. These experiments considered the community with fixed five followers. From Figures 10 to 14, we use violin plots for better visualization of the data distribution (shards, transactions, memory size, and time) with the mean (in purple color) and median (in red color) distribution. First, we explain the meaning of a violin plot. Consider Figure 12A. The violin plot shows the minimum, maximum, mean, and median number of shards in a block. For instance, in this plot, for the entry with 100 transactions per block as shown in the *x*-axis, the details are as follows: minimum 1, maximum 99, mean 36.19, and median 40. In all the plots mean is shown in purple while the median is shown in red. Here, the mid-way bulge in the violin plot represents the maximum frequency of occurrence of the shards. Having explained its meaning, we now analyze the plots.

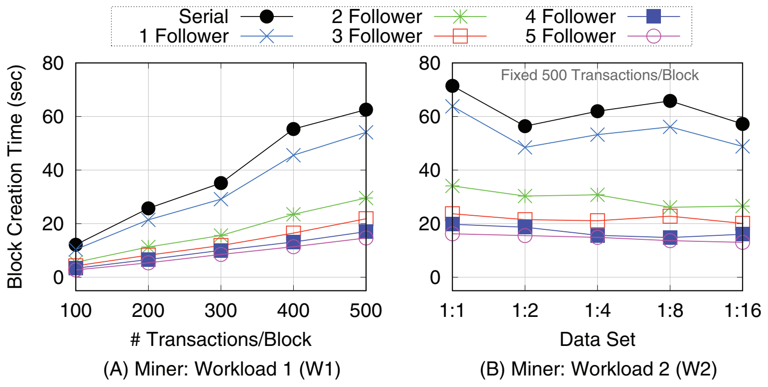


FIGURE 8 Average end-to-end block creation time, including the time to find PoW by community miner

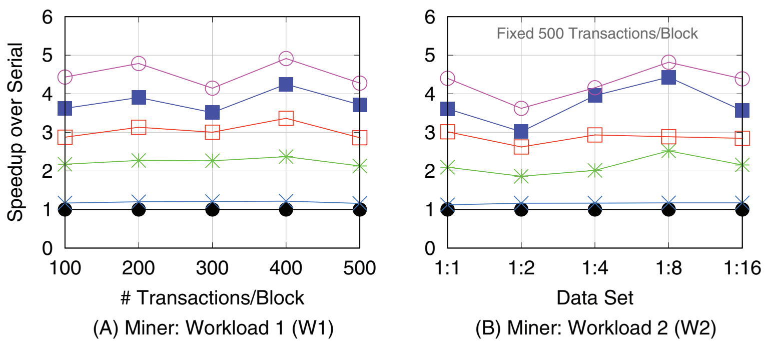


FIGURE 9 Average end-to-end block creation speedup by community miner over serial miner

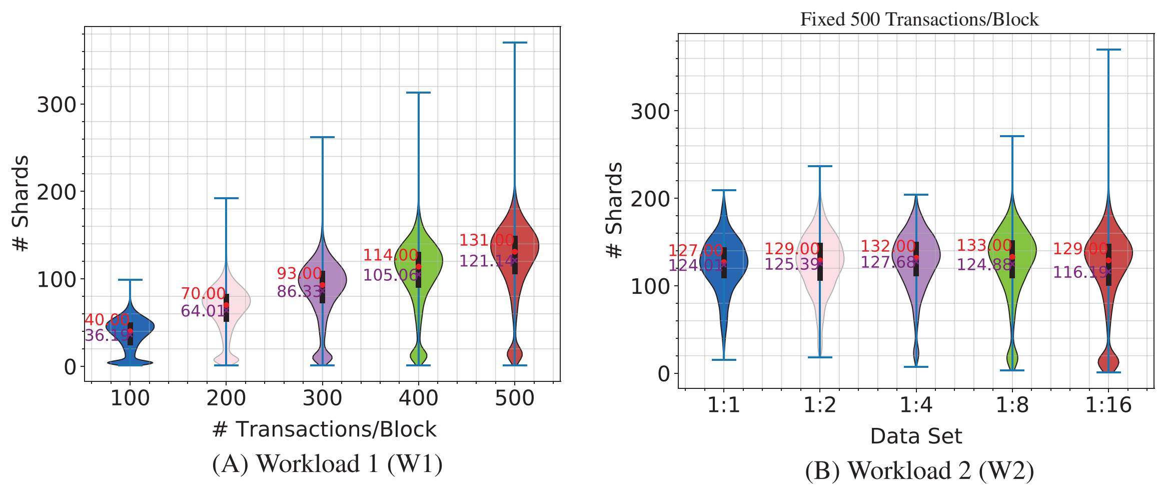


FIGURE 10 Number of shards with varying transactions per block and varying data set (ρ)

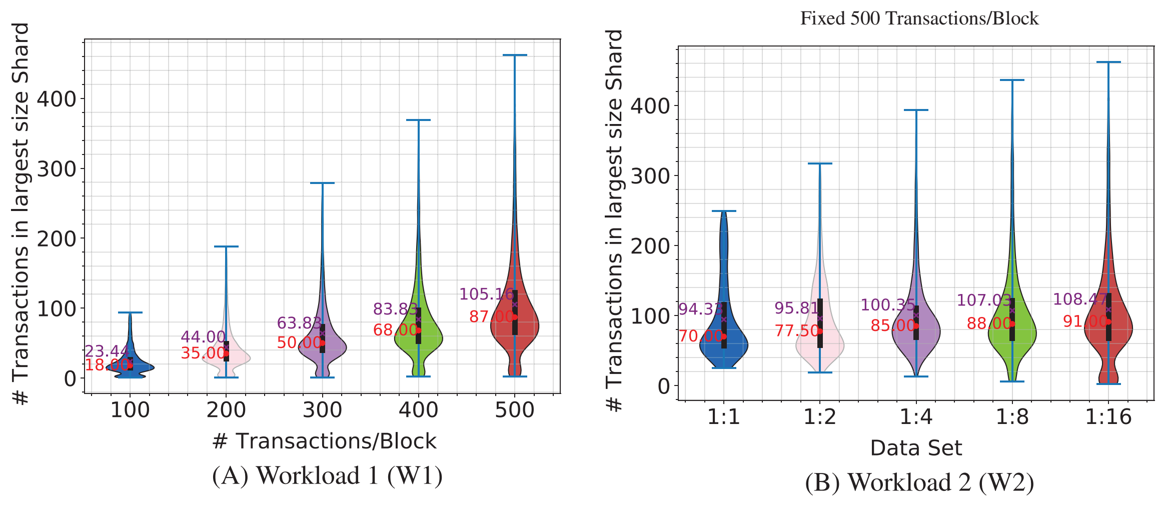


FIGURE 11 Number of transactions in a shard with varying transactions per block and varying data set (ρ)

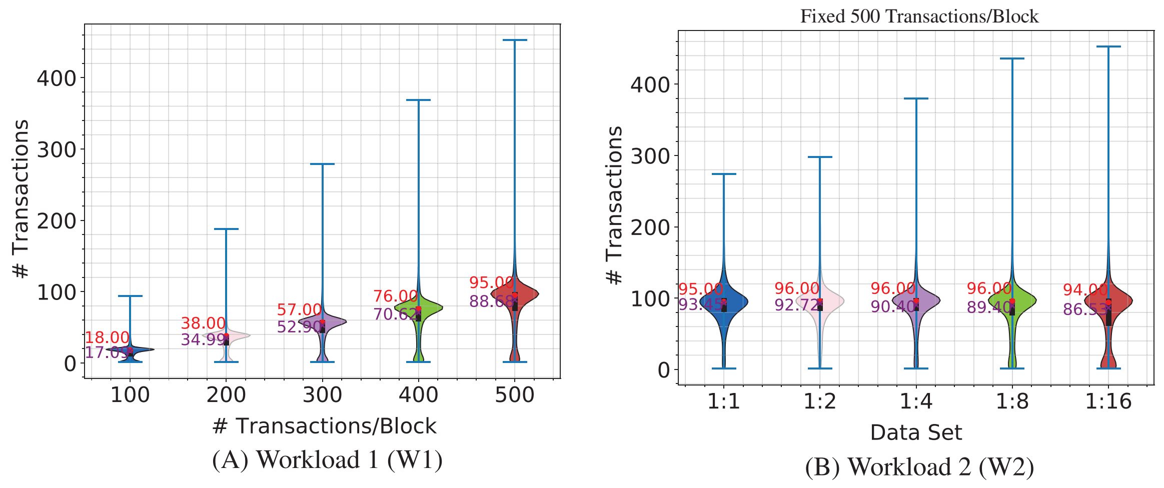


FIGURE 12 Number of transactions allocated to a follower with varying transactions per block and varying data set (ρ)

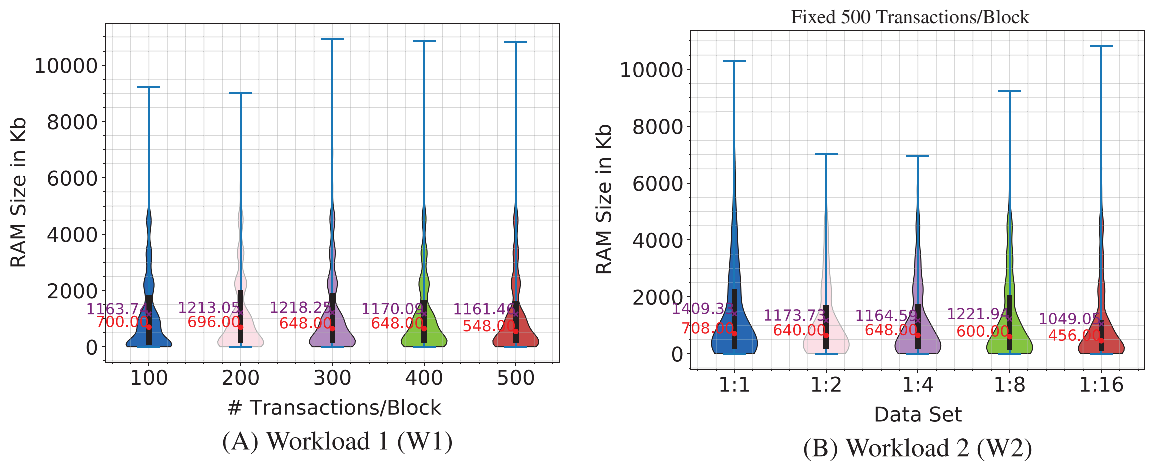


FIGURE 13 Memory utilized by followers during execution with varying transactions per block and varying data set (ρ)

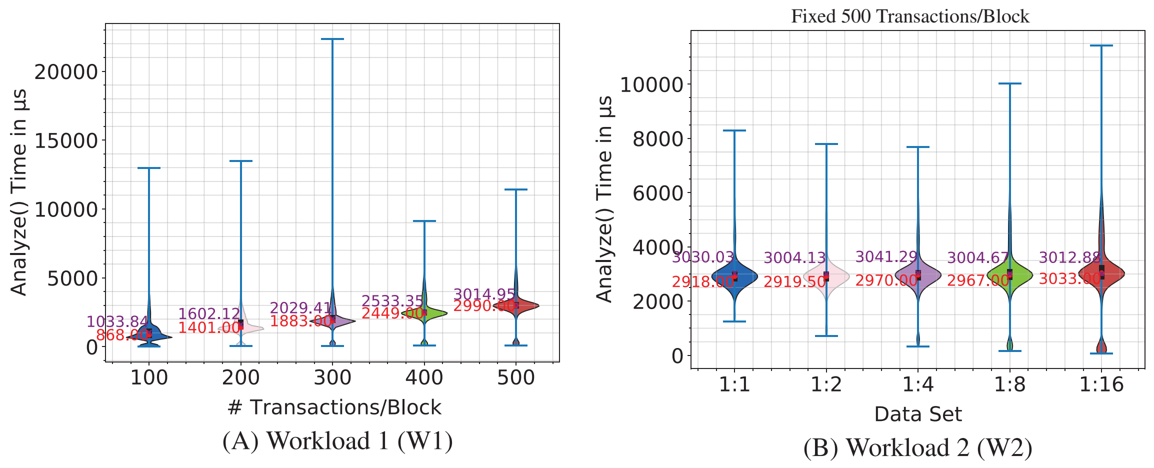


FIGURE 14 Time taken by `Analyze()` algorithm with varying transactions per block and varying data set (ρ)

To determine available parallelism within a block, the violin plot in Figure 10 shows the number of shards per block on both workloads. Figure 10A shows the number of shards on Workload 1, Figure 10B on Workload 2 with varying ratio ρ, and Figure 12 shows the number of transactions allocated to a follower. The larger the number of shards in a block, the higher the possibility of parallelism. The number of shards per block increases with the increasing number of transactions in a block on Workload 1. Nevertheless, on Workload 2, it remains approximately the same due to the fixed number of transactions.

It must be observed that more the number of shards better is the parallelism. Thus, if all the transactions get grouped into a few shards then there is not much parallelism. We observe this to not be the case in our experiments. Since we have used real historical transactions from the Ethereum blockchain, this shows that the real-world blockchain applications exhibit considerable amount of parallelism.

When the number of shards is higher than the community size, our algorithms load balances between the community followers reasonably well. Remarkably, the number of blocks with very less number of shards is not high which reinforces our above observation that real-world blockchain applications exhibiting good amount of parallelism. The maximum shards on both the workloads are ≈370. While the average number of shards in Workload 1 increases from ≈40 to ≈131 when transactions vary from 100 to 500 per block, respectively.

Figure 11 shows the violin plot of the number of transactions in the largest shard with varying number of transactions per block (Figure 11A) and varying ρ (Figure 11B) to demonstrate the skewness present within a shard and blocks. The larger the number of transactions in the largest shard (skewed), the lower the block parallelism. We can observe in Figure 11 that the number of transactions increases in maximum shard in both workloads. The increase in transactions with varying ρ on Workload 2 is relatively significant compare to Workload 1. It indicates that the correlations between transactions often escalate when monetary transaction increases in the block. As shown in Figure 12, after the load balancing, the average number of transactions allocated to a follower is balanced. Hence all the followers get approximately even load (we have five followers in the community).

We observed that the maximum number of shards is ≈ 370 in a block with 500 transactions in Workload 1. On average, a shard with a maximum number of transactions is ≈460 in 500 transactions block when ρ is $\frac{1}{16}$. The number of shards and number of transactions (in the maximum size shard) increases with an increase in the number of transactions per block (Workload 1) and ratio ρ (Workload 2), respectively.

3.4.4 | Performance overhead analysis

The analysis of the average memory size taken by the followers during the execution of the transaction and the time taken by the leader for sharding block transactions (i.e., time taken by `Analyze()` (Algorithm 1)) using violin plots is discussed in this section.

The maximum memory used by followers increases with an increasing number of transactions in the block, which can be seen in the violin plot of Figure 13A. This is as expected, because additional transactions in the block may take extra space to store data as well more space during execution. However, the average memory size remains steady. As shown in the violin plot of Figure 13B, with increasing ratio ρ, the average memory size decreases; this may be because non-smart contract (monetary) transactions are less expensive in computation and latency than smart contract function calls, hence take lesser space. In contrast, the maximum memory size in Workload 2 reaches ≈10,000 kB that is relatively closer to maximum memory size in Workload 1.

The time taken by `Analyze()` algorithm can be seen in Figure 14. It is utilized to find shards using static analysis as a graph problem. The algorithm is explained in Section 2.1.3. We use microseconds (μs) here in Figure 14 for visualization purposes since the analysis algorithm takes significantly less time than the execution time of the transactions. As shown in Figure 14A, analysis time increases with increasing transactions in the block since the time taken by graph construction and WCC composition to find different shards increases with the number of transactions. However, the number of transactions in Workload 2 with varying ratio ρ is fixed to 500 per block; consequently, the average time taken by the static analysis is almost comparable as shown in Figure 14B.

3.4.5 | Throughput analysis

The throughput analysis of the proposed *DiPETrans* blockchain on community configuration for parallel transaction execution and serial execution is discussed here.

Figure 15 shows the throughput trend on the Workload 1 and Workload 2. Throughput increases with the increasing number of transactions per block as well it increases with the increase in the non-smart contract (monetary) transactions per block on Workload 2. The gain in throughput on Workload 2 is relatively more significant than that of on Workload 1. This gain implies that non-smart contract (monetary) transactions are less expensive in computation than smart contract transactions; therefore, more transactions can be executed per second and hence higher latency w.r.t these transactions.

Further, as shown in Figure 15A, the throughput for serial execution increases with the increasing number of transactions to 300 transactions per block and reaches a maximum of 900 tps (transactions per second); after that, there is a drop-down in throughput. However, this is not the case with community-based parallel execution in the proposed approach; it keeps increasing with the increasing number of transactions per

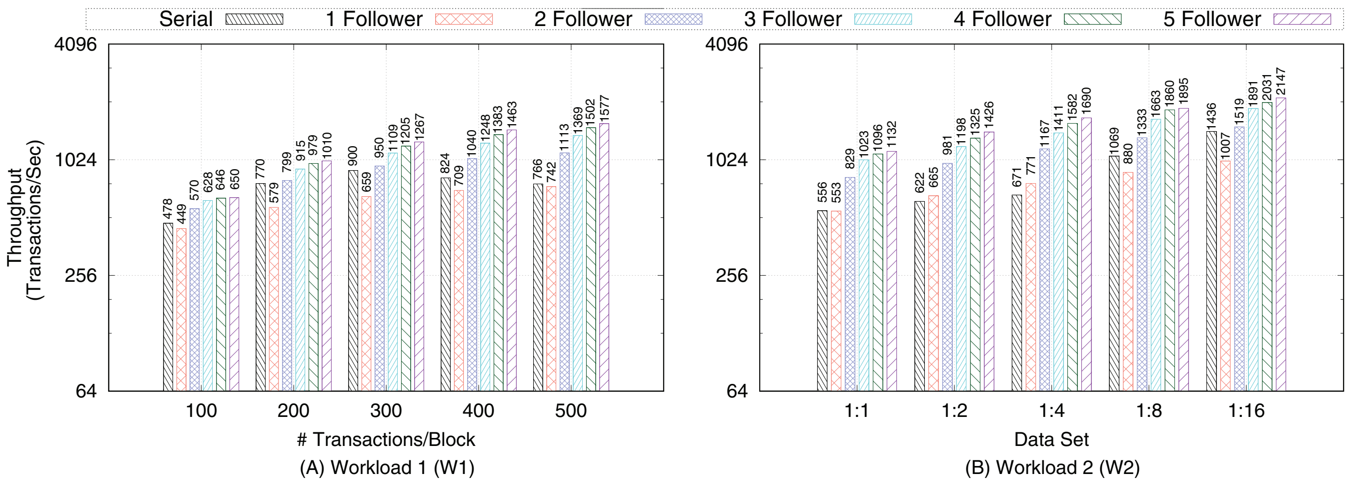


FIGURE 15 Throughput with varying transactions per block and varying data set (ρ)

block and followers in the community, which confirms that *DiPETrans* improves the throughput. The maximum throughput on Workload 1 is 1577 tps in a community with five followers at 500 transactions per block, which is 2.05× higher than that of serial execution. Nevertheless, this difference narrows down to 1.49× on Workload 2 as shown in Figure 15B, where parallel execution achieves a maximum throughput of 2147 tps when ratio $\rho = \frac{1}{16}$. However, the sweet spot of maximum throughput by parallel approach concerning serial is at 2.52× with 1690 tps on Workload 2 when $\rho = \frac{1}{4}$. This implies that the proposed approach yields maximum benefit when a block consisting of a small number of monetary transactions. Since contractual transactions are computation-intensive and executing independent contractual transactions in parallel will increases the throughput.

3.4.6 | Optimal community size

As we saw from the complexity analysis in Section 2.1.4, the choice of an optimal community size ($c = f + 1$), which has 1 leader and f followers, depends on several parameters, including the number of transactions per block, the mix of contractual and non-contractual transactions per shard, the number of shards formed from a block, and so forth. In an ideal scenario, one would have a large number of transactions per block (n) to amortize the overhead costs across transaction execution, have many contractual transactions that are independent and hence benefit from fully parallel execution (high value of ρ), form as many shards (m) as the number of followers (f) and have an equal number of transactions in each shard to have good load balancing. Given the heterogeneity and the variation of transaction and their dependencies over time, that is, n, m, and ρ vary per block, it is difficult to identify the best size f of the community.

One can observe these values in the transaction blocks over time to form an empirical estimate of what values of f would work well. For example, one could experimentally identify the average shards formed per block and then set the community size to be equal to this average value to maximize parallelism. However, this can also lead to under-utilization of the followers. Specifically, if there is a skew between the number of transactions in the largest shard and the rest of the shards, or if one follower is assigned shards with many more transactions than the other followers, then this slowest follower/largest shard will cause the others to be idle after executing transactions in their shards and thus limiting the resource usage of the community.

We analyze the effect of the community size and workloads on the utilization of the followers. For a community of size $f = 5$, Figure 16 reports the time taken by the follower with the largest shard/most transactions (*maximum execution time* bar), the average time to a shard by a follower (*average execution time* bar), and the cumulative idle time for which the remaining 4 followers are waiting for the slowest follower to complete execution once they have completed their shard executions (*accumulative idle time* bar). With an optimal community size, the idle time will be minimized, tending towards zero. In such a scenario, the average execution time will be similar to the maximum execution time.

Figure 16A reports these values for the workload W1 introduced earlier. With fewer number of transactions per block of $n = 100$ across a mix of ρ values, the idle time of the followers is higher (35 ms) relative to the average execution time (23.4 ms). However, this difference decreases as we increase the number of transactions per block to $n = 500$. This is because with more transactions, there is a greater number of independent transactions or WCCs likely to be formed and hence a better chance of balancing the load across the followers. This is also seen from the % difference between the maximum and the average times, which reduces from 28% to 16%.

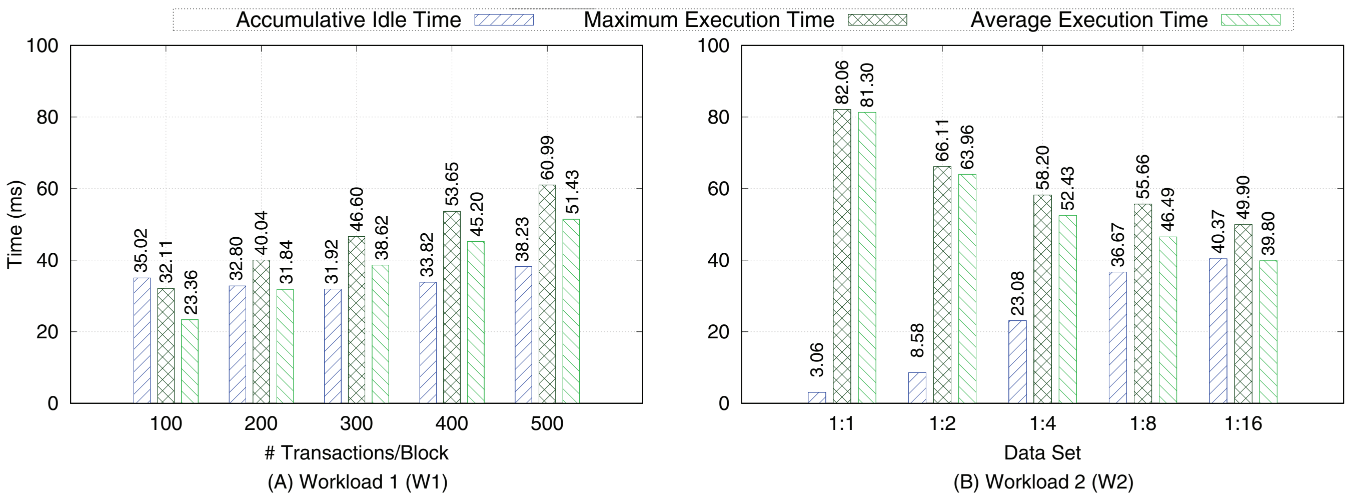


FIGURE 16 Transaction execution time by a follower and accumulative followers idle time with varying transactions per block and varying data set (ρ)

In Figure 16B which reports the timing values for workload W2 with $n = 500$ transactions per block but varying the mix of transaction types, we see that the idle time increases with ρ. When we have more contractual transactions with $\rho = \frac{1}{1}$, there are fewer dependencies from the non-contractual monetary transactions, allowing for better load balancing across followers. When the number of monetary transactions per block increases to $\rho = \frac{1}{16}$, the dependencies increases, consequently increasing the shard sizes and the potential skew across them. For example, with $\rho = \frac{1}{1}$, the difference between the maximum and average times is only 1% while this grows to 20% for $\rho = \frac{1}{16}$.

While these types of analysis can be used to guide the selection for a community size, determining the ideal size is challenging due to the inherent variability of n and ρ. In future, one could conceive of a machine-learning technique to dynamically determine the optimal community size and elastically provision such followers on-demand.

In addition to these experiments, we have done few additional experiments. The additional results are presented as follows in the appendix: Additional results for transaction execution time and speedup in Appendix C. Block execution time (end-to-end time) at miner in Appendix D. For varying number of transaction from 500 to 2500 in Appendix E.

4 | RELATED WORK

This section presents an overview of existing techniques to improve the throughput and performance of the blockchains. We first give a brief overview of the work on concurrent execution of the smart contracts then presents the work on sharding based techniques.

4.1 | Multi-threaded techniques

Several challenges prevent widespread adoption of the public blockchain, such as high transaction fees, poor throughput, high latency, and limited computation capacities[5] as explained in Section 1. Also, most blockchain platforms execute the transaction serially, one after another, and fail to exploit the parallel execution provided by current-day multi-core systems.[2,9] Therefore to improve the throughput and to utilize parallelism available with multi-core systems, researchers have developed solutions to execute the transactions in parallel.

For the concurrent execution of the smart contract within the single multi-core system, Dickerson et al.[2] and Anjana et al.[10,11] proposed STM based multi-threaded approaches. They achieve better speedup over serial execution of the transactions. However, their techniques are limited to concurrent smart contract transaction executions and based on the assumption of non-nested contract calls. Saraph and Herlihy[17] perform an empirical analysis and exploited simple speculative concurrency in Ethereum smart contracts using a lock-based technique. They group the transactions of a block into two bins—one with non-conflicting transactions that can be executed concurrently, while another with conflicting transactions that are executed serially. Zhang and Zang[22] propose a multi-version concurrency control based concurrent validator in which miner can use any concurrency control protocol to generate the read-write set to help the validators to execute the transactions concurrently. In Reference 23, Bartoletti et al. presented a statistical analysis-based theoretical perspective of concurrent execution of the smart contract transactions.

In contrast, the solution we propose focuses on the distributed computing power across multiple servers to parallelly execute and verify the block transactions and determine the PoW. This complements concurrency techniques within a single machine.

4.2 | Sharding-based techniques

Mining pools use distributed computing power of multiple peers to find the PoW in parallel and share the incentive based on pre-agreed mechanisms, for example, proportional, pay-per-share, and pay-per-last-N-shares.[6,7] Both centralized and decentralized mining pools are practically used in Bitcoin and Ethereum. For example, in the Bitcoin, ≈95% of the mining power resides with less than 10 mining pools, while 6 mining pools hold ≈80% of the mining power in Ethereum.[8] Our work goes beyond executing the PoW in parallel and utilizes the pool to execute and verify the transactions parallelly, without affecting the correctness.

Recent studies have focused on sharding based techniques to improve the blockchain's throughput and scalability. A majority of these divide the network into multiple clusters and work on the assumption that there is no malfunction in most of the nodes, for example, there are no more than t byzantine nodes in a cluster with n nodes, where $n \gg t$. Additionally, several sharding solutions use a leader-based BFT consensus protocol, including Tendermint,[24] Elastico,[25] Hyperledger Fabric,[11] and RedBelly.[26] However, in the proposed work, we do not partition the network into different clusters. Instead, a node itself serves as a representative for a cluster of distributed resources. Moreover, there is no need to change underlining blockchain consensus protocols, allowing drop-in replacement of our proposed solution into existing platforms.

Elastico[25] is a sharding-based open blockchain protocol where participants join various clusters at random. The PBFT consensus protocol is used by a leader-based committee to verify the cluster transactions and add a block to the global chain stored by all nodes. However, running PBFT on a large number of nodes reduces its performance and increases the probability of failure on a few nodes. Hyperledger Fabric,[11] the most widely used permissioned blockchain platform, introduces the concept of channels. Multiple nodes in the fabric form clusters called channels and the users submit their transactions to their channel. The channel nodes maintain the partitioned state of the whole system as they execute transactions. Different channels process the transactions in parallel to improve the performance. RedBelly[26] blockchain performs a partially synchronous consensus run by permissioned nodes to create new blocks, while permissionless nodes issue transactions. Usually, a transaction in a cluster is verified by all the nodes in the cluster. However, in RedBelly, this verification is done by between $t + 1$ to $2t + 1$ nodes in the cluster to improve throughput by committing more transactions per consensus instance, where t is the maximum number of byzantine nodes in the cluster. RapidChain[27] is a completely trustless sharding-based blockchain that achieves high throughput through inter-shard transaction execution via block pipelining and gossiping protocol. However, it also requires reconfiguration by the block creators for robustness. OmniLedger[28] offers a protocol to assign nodes to different clusters and processes intra-shard transactions using a lock-based atomic consensus protocol based on a partial-synchrony assumption. AHL[29] proposes a trusted hardware-assisted solution to reduce the nodes in a cluster. Nodes are randomly assigned to clusters and can ensure high security much fewer nodes per cluster than OmniLedger. SharPer[30] uses flattened consensus protocol and maintains the chain as a directed acyclic graph where each cluster stores only a view of the chain and supports intra-shard and inter-shard transactions.

Another closely related work by Leshkowitz et al.[31] proposes a leader–follower paradigm where the miner (leader) executes the block transactions serially and provides the information (write sets) to perform the validation in parallel to one or more committees of blockchain nodes in a permissioned blockchain setting. Each block is divided into multiple segments of sequential transactions, each of which is executed concurrently by a node in a validation committee. The validation committees with a fixed number of nodes in each are formed by partitioning the nodes of the blockchain network, and multiple committees may validate the same block to ensure correctness by the leader. This approach poses several downsides. Since adjacent transactions are segmented without regard to inter-dependencies, parallel execution of dependent transactions by different nodes of a committee can lead to a FBR error.[9] Further, having fixed size committees formed from existing nodes in the network limits flexibility. In contrast, our approach (1) uses sharding to form independent transactions, which prevents incorrect validation of dependent transactions, (2) employs parallel execution during both mining and validation phases using communities (committees) that can have a dynamic size, and (3) exposes only the leader of the community to the public blockchain network as a single logical node while the followers remain private.

In summary, the UTXO model is used to achieve the atomicity of cross-shard transactions without the use of a distributed commit protocol in OmniLedger,[28] RedBelly,[26] and RapidChain.[27] However, RapidChain fails to achieve isolation, and OmniLedger causes blocking for cross-shard transactions. A few approaches support transactions that are cross-shard while others do not. Compared to AHL,[29] SharPer[30] uses the account-based model and allows cross-chain transactions using a global consensus protocol based on PBFT to achieve correctness. In contrast, Hyperledger Fabric[11] also supports the account-based model, but requires a trusted channel among the participants to execute cross-shard transactions. Moreover, almost all existing blockchains that focus on sharding divide the network into multiple clusters and process transactions independently, using variants of the BFT consensus protocol or atomic commit protocol to increase transaction throughput and achieve scalability for the dependent transaction.

In our proposed approach, we do not partition the network into different clusters. Instead, we follow a leader–follower approach among the distributed clusters of cooperating nodes, where the leader serves as a representative node in the existing blockchain network such as Bitcoin and Ethereum. The leader performs the static analysis of the transactions it receives to create shards, while the followers perform the computation over the different shards concurrently. The PoW is also solved in parallel. This can be both permissioned or permissionless and can be done independently for the mining and the validation phases in a transparent manner. The coordination overheads are minimal, as all nodes within a cluster are assumed to be trusted. These allow *DiPETrans* to be trivially adopted within existing blockchain systems (permissioned or permissionless) and benefit from parallel execution without the complexity of additional distributed consensus protocols while ensuring correctness.

5 | CONCLUSIONS AND FUTURE WORK

In this article, we propose a distributed leader–follower framework *DiPETrans* to execute transactions of block parallelly on multiple nodes that are part of the same community. We test our prototype on actual transactions extracted from Ethereum blockchain. We achieve gains in performance proportional to the number of followers. We also see performance gains in the execution time of contract and monetary transactions. We evaluate *DiPETrans* on various workloads, where the number of transactions ranges from 100 to 500 in a block, with a varying ratios of contract and monetary transactions. We observe that the speedup often increases in a distributed setting with an increase in the number of transactions per block, thus increasing the throughput. We also observe that a block execution time increases with the number of contract calls, and the speedup increases linearly with the community size.

There are several directions for future research. Assuming the number of transactions will increase over time, we can conceive a community that proposes multiple blocks in parallel. An alternative way to boost performance is to use software transaction memory (STM) for follower nodes and run the transactions concurrently in each follower using multi-cores rather than serially. In this work, we assume that there are no nested contract calls, but in practice nesting is common with contracts of blockchains. So incorporating nesting is in our framework can be a useful future work.

We have seen performance gains with just 5 followers in the community. It would be interesting to see how the system scales and the peak speedup with hundreds or thousands of transactions per block and a larger number of community followers. Apart from the above optimization, we are also planning to adopt a wholly distributed approach within the community instead of the leader–follower approach that is resilient to failures and other faults. We plan to integrate it with Ethereum blockchain by deploying a *DiPETrans* community smart contract.

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DATA AVAILABILITY STATEMENT

Data openly available in a public repository that does not issue DOIs. Source code is available on Github at: https://github.com/dream-lab/DiPETrans. Full technical report is available at: https://arxiv.org/abs/1906.11721.[20]

ENDNOTE

*The additional experiments and raw values for these plots are reported in the Appendix.

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APPENDIX A. BACKGROUND

In most popular blockchain systems such as Bitcoin[1] and Ethereum,[3] transactions in a block are executed in an ordered manner, first by the miners later by the validators.[2] When a miner creates a block, it typically chooses transactions from a pending transaction queue based on their preference, for example, higher priority to transactions with higher fees. After selecting the transactions, the miner (1) serially executes the transactions, (2) adds the final state of the system to the block after execution, (3) next finds the PoW, and (4) broadcasts the block in the network to other peers for validation to earn the reward. A PoW is an answer to a mathematical puzzle in which miners try to find a block's hash smaller than the given difficulty.

Later, after receiving a block, a node validates the contents of the block. Such a node is called the validator. Thus, when a node N_i is a block-producer, every other node in the system acts as a validator. Similarly, when another node N_j is the miner, then N_i acts as a validator. The validators (1) re-execute the transactions in the block received serially, (2) verify to see if the final state computed by them is the same as the final state provided by the miner in the block, and (3) also validate if the miner solved the puzzle (PoW) correctly. The transaction re-execution by the validators is done serially in the same order as proposed by the miner to attain consensus.[2] After validation, if the block is accepted by the majority (accepted by more than 50%) of the validators, the block is added to the blockchain, and the miner gets the incentive (in the case of Bitcoin and Ethereum).

Further, blockchain is designed in such a way that it forces a chronological order between the blocks. Every block which is added to the chain depends on the cryptographic hash of the previous block. This ordering based on cryptographic hashes makes it exponentially challenging to make any change to the previous blocks. To make any small change to already accepted transactions or a block stored in the blockchain requires recalculation of the PoW of all subsequent blocks and acceptance by the majority of the peers. Also, if two blocks are proposed simultaneously and added to the chain, they form a *fork*, the branch with the longest chain is considered the final. This allows mining to be secure and maintain a global consensus based on processing power.

APPENDIX B. PROPOSED ALGORITHMS

This section describes the proposed algorithms and a short description of them.

Algorithm 3: `LeaderMinerTask`()—The *LeaderMiner* starts block creation by calling `CreateBlock`() (Algorithm 5). The candidate block consists of the block number, nonce, previous hash, miner detail (coin base address), transaction list, and so forth. `Analyze`() (Algorithm 1) is used to analyze the candidate block transactions for sharding. The leader receives a response *sendTxnsMap* from `Analyze`(), which consist a map of *followerID* and transactions list. Each follower is allocated a unique id during the initialization of the leader server. The leader connects to the follower by

Algorithm 3. `LeaderMinerTask`(ethereumData)

```
Data: ethereumData, followerList, dataItemMap
Result: blockchain (blockList)
35 Procedure LeaderMinerTask(ethereumData):
36     Block block;
37     for data ∈ ethereumData do
           // Creates candidate block.
38         block = CreateBlock(data);
39         if block.txnsList.size() > 0 then
               // Identify disjoint sets of txns (Weakly Connected Components).
40             sendTxnsMap = Analyze(block.txnsList);
               // Parallel call to each follower to assign transactions.
41             for follower ∈ followerList do
42                 ConnectFollower(follower, sendTxnsMap);
43             end
               // Wait till all follower execution completes.
44         end
           // Start Block Mining
45         miningStatus = false;
46         for follower ∈ followerList do
               // Parallel call to each Follower to mine block.
47             FollowerMineBlock(follower, block);
48         end
49         while !miningStatus do
50             wait();
51         end
           // Broadcast the block for validation to all other peers.
52         blockchain.append(block);
53     end
54 return blocklist
```

creating parallel threads with a call to `ConnectFollower`() (Algorithm 8). The leader waits for the followers to complete the transaction execution. So as soon as the leader receives the *follower response (SResponse)*, it makes changes to its state in *dataItemMap*.

After transaction execution, the leader starts mining (determining PoW) by setting *miningStatus* to *false*. For this, the leader distributes the task among the followers to mine the block using an asynchronous call to `FollowerMineBlock`() (Algorithm 7). The leader calls on each follower to mine from a different starting nonce in sequence. In this way, search space is distributed among the followers for PoW calculation. The leader waits until the *miningStatus* turned out to be true by a follower. The follower who finds the correct PoW sends the information to the leader. Finally, the leader saves the nonce and broadcasts the block in the network for validation.

Algorithm 4: `DefaultValidator`()—When a validator receives a block for validation, it re-executes the transactions. It then matches the final state of the *dataItemMap* state. Since in this approach, dependency (shard) information is not added to the block by the miner, the leader validator needs to call `Analyze`() to determine the disjoint sets of transactions. Then the leader validator follows the same approach as the miner to distribute transactions to the followers and waits for all followers to complete. The leader validator does not have to mine the block. The leader validator updates its *dataItemMap* state based on the responses from the followers. Finally, it verifies its *dataItemMap* state with the block's *dataItemMap* state. If *dataItemMap* state matches after successful execution of a block's transaction, then it checks for PoW by verifying $hash(block) < difficulty$. If both the checks come out to be successful, an acceptance message is propagated in the network. Otherwise, the validator rejects the block. After majority acceptance or consensus, the block is added to the *blockchain*.

`SharingValidator`()—In this function, sharding information is added to the block by the miner, so the leader validators do not call `Analyze`() at *line 3* in Algorithm 4. Therefore, the analyze function's overhead can be avoided, and the validator utilizes the analysis work done by the miner for

Algorithm 4. `LeaderValidator`(block)

```
Data: block
Result: blocklist
55 Procedure LeaderValidator(block):
56     if block.txnsList.size() > 0 then
           // Identify disjoint sets of txns (Weakly Connected Components).
57         sendTxnsMap = Analyze(block.txnsList);
           // Parallel call to each follower to assign transactions.
58         for follower ∈ followerList do
59             ConnectFollower(follower, sendTxnsMap);
60         end
           // Wait till all follower execution completes.
61         reject = false;
           // Verify PoW.
62         if hash(block) > difficulty then
               // PoW is incorrect.
63             reject = true;
64         else
               // Verify dataItemMap with block's dataItemMap state.
65             for adr, value ∈ block.dataItemMap do
66                 if dataItemMap[adr] != value then
67                     reject = true;
68                     break;
69                 end
70             end
71         end
72     end
       // If Accepted than add to local blockchain.
73     if !reject then
74         blockchain.append(block);
75     end
76 return
```

parallel execution. So, in the *Sharing Validator*, the *LeaderValidator* deterministically assigns the different shards based on the dependency information in the block to the different *FollowerValidator* along with the current state of the data items from its local chain for transaction execution. The rest of the functionality of this algorithm is the same as the *Default Validator*.

Algorithm 5: `CreateBlock`()—In this function, the leader creates the candidate block by picking pending transactions from the pending transactions pool. The leader also assigns the block number, previous hash, and miner (coin base address) to the block. There can be some uncle blocks, which are valid blocks, and the miner who proposed those blocks deserves an incentive for their work. If these blocks are added by the upcoming blocks (<8), also called nephew blocks, they are given partial incentives based on Equation (B1). Some incentive based on Equation (B2) is also given to the miner who adds the uncle blocks. The maximum limit on the inclusion of uncle blocks is 2.

$$nephewMinerReward = \frac{baseReward}{32} \tag{B1}$$

$$uncleMinerReward = \frac{(uncleBlockNumber + 8 - nephewBlockNumber) * baseReward}{8}. \tag{B2}$$

Algorithm 5. `CreateBlock`(data, prevHash)

```
Data: data, prevHash
Result: block
Procedure CreateBlock(data, prevHash):
    Block block ;
    block.number = data.number;
    block.prevHash = prevHash;
    block.miner = data.miner;
    // creates candidate block
    for tx ∈ data.txns do
        Transaction txn(tx.txID, tx.to, tx.from, tx.value, tx.input, tx.creates);
        block.txnsList.append(txn);
    end
    for u ∈ data.uncles do
        Uncle unc(u.number, u.miner);
        block.unclesList.append(unc);
    end
return block
```

Algorithm 6. `MiningStatus`(block, nonce, number)

```
Data: block, nonce, number
Result: miningStatus
Procedure MiningStatus(block, nonce, number):
    if block.number == number && !miningStatus then
        block.nonce = nonce;
        miningStatus = true;
    end
return miningStatus
```

Algorithm 6: `MiningStatus`()—A follower calls this function to send the block's nonce value to the leader and signal that mining has completed. In this function, the follower checks for the block number on which the leader is working, and if the block number and the *miningStatus* are not true. Then, the follower updates the nonce value of the block and sets *miningStatus* to true as soon as the leader notices a change in the *miningStatus* variable and comes out of the wait loop. Then they starts working on the next block after sending the current block for its inclusion in the blockchain and verification by validators.

Algorithm 7: `FollowerMineBlock`()—In this function, followers receive the starting nonce and interval along with the block to find the PoW. The PoW is found when $hash(block) < difficulty$ is found for a particular value of nonce. Otherwise, a nonce is incremented by the interval to try again in an infinite loop. The difficulty we have set for now takes approximately 15 s to mine a block, which is close to the current average time of Ethereum block execution. The actual difficulty is much greater than what we are using, considering the resources deployed by miners to find PoW.

Algorithm 8: `ConnectFollower`()—In this function, followers receive the starting nonce and interval and the block to find the PoW. The PoW is found when $hash(block) < difficulty$ is found for a particular value of nonce. Otherwise, a nonce is incremented by the interval to try again in an infinite loop. The difficulty we have set takes approximately 15 s to mine a block, which is close to the current average time of Ethereum block execution. The actual difficulty is much greater than what we are using, considering the resources deployed by miners to find PoW.

Algorithm 9: `FollowerRecvTxns`()—While executing `FollowerRecvTxns`() (i.e., Algorithm 9), the follower receives the transaction list and associated *dataItemMap* state from the leader. The follower first identifies smart contract and non-smart contract calls (transactions). Suppose the

Algorithm 7. `FollowerMineBlock`(block, nonce, interval, difficulty)

```
Data: block, nonce, interval, difficulty
Result: nonce
97  Procedure FollowerMineBlock(block, nonce, interval, difficulty):
98      while true do
99          if hash256(block) < difficulty then
100             MiningStatus(nonce, block.number);
101             break;
102         end
103         nonce += interval;
104     end
105 return nonce
```

Algorithm 8. `ConnectFollower`(follower, sendTxnsMap)

```
Data: follower, sendTxnsMap
Result: dataItemMap
106 Procedure ConnectFollower(follower, sendTxnsMap):
        // Identify Associated dataItemMap for each follower.
107     for tx ∈ sendTxnsMap[SID] do
108         localDataItemMap[tx] = dataItemMap[tx];
109     end
        // Send txns to follower to execute, receive updated state.
110     SResponse = FollowerRecvTxns(sendTxnsMap[Follower], localDataItemMap);
        // Update leader's dataItemMap state.
111     for adr, dataItem ∈ SResponse.dataItemMap do
112         dataItemMap[adr] = dataItem;
113     end
114 return dataItemMap
```

transaction is a smart contract call. In that case, the transaction is executed by invoking `CallContract`() to execute the respective smart contract method. Otherwise, non-smart contract calls are considered as monetary exchanges and executed within the scope of this function. For `CallContract`() transaction execution, we have implemented the top 11 functions calls in Ethereum, which cover 80% of real transactions of block numbers between 4,370,000 and 4,450,000.

APPENDIX C. ADDITIONAL RESULTS AND OBSERVATION FOR TRANSACTION EXECUTION TIME AND SPEEDUP

This section presents the experimental analysis for transaction execution time for Workload-3 and the speedup achieved in transaction execution by the parallel miner and validator over serial. First, we present the analysis for transaction execution time for Workload-3. Then we present the additional analysis for speedup on Workload-1, Workload-2, and Workload-3.

C.1 Transaction execution time analysis

Workload-3: Figure C1 shows the analysis for a fixed number of transactions (500) per block with varying community size. This workload is designed to see how each block's transaction ratio (contract call: monetary transaction) will impact the performance. We can observe in Figure C1A–C that 1 follower is performing the worst due to the overhead of static analysis and communication with the leader. Other follower configurations from 2 to 5 outperform serial, and execution time decreases as the number of followers increases. Also, the smaller the number of contractual transactions per block, the better the performance will be. This is because of the external method called the contractual transaction. Similar to Workload-1 and Workload-2, also there is no much performance difference in *Sharing Validator* and *Default Validator*.

Algorithm 9. `FollowerRecvTxns`(txnsList, dataItemMap)

```
Data: txnsList, dataItemMap
Result: SResponse
115 Procedure FollowerRecvTxns(txnsList, dataItemMap):
        // Execute txns serially.
116     for tx ∈ txnsList do
            // Smart Contract txn.
117         if tx is contractCall then
118             CallContract(tx);
            // Non-Smart Contract txn.
119         else if tx.value ≤ dataItemMap[tx.from].value then
120             dataItemMap[tx.fromAddress].value -= tx.value;
121             dataItemMap[tx.toAddress].value += tx.value;
122         else
                // Invalid txn: txn execution failed!
123         end
124     end
125 return SResponse
```

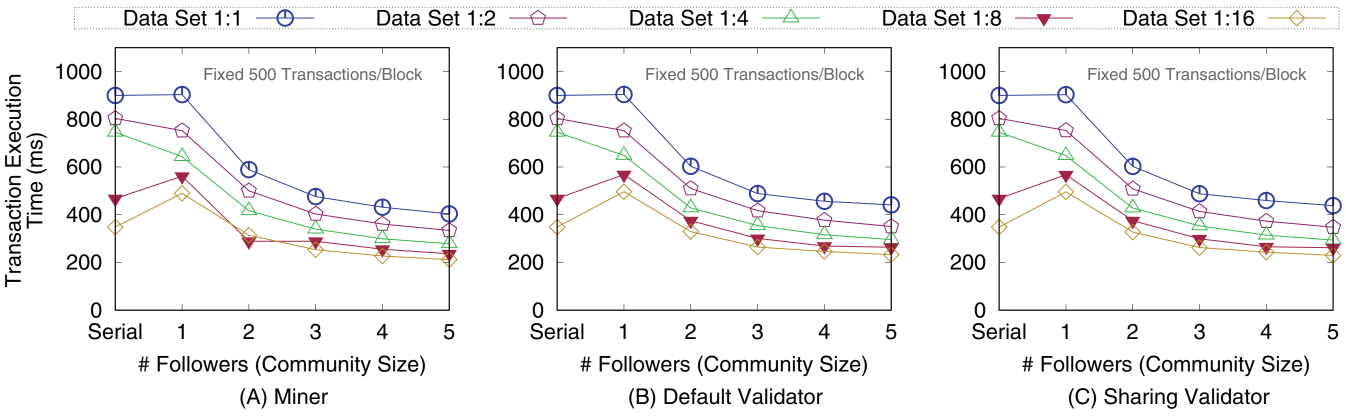

FIGURE C1 Workload-3: Average transaction execution time by miner (omitting time to find PoW) and validator

C.2 Speedup analysis

Here we present the result analysis for all three workloads based on speedup achieved by the parallel miner and the validator over the serial miner and validator.

Workload-1: Figure 5 shows the average transaction speedup achieved by the miner (omitting time to find PoW) and validator. As shown in Figures 5A–C, the mean speedup increases as the number of transactions per block increases. Also, one follower is performing worst due to the small overhead of static analysis and communication with the leader. Other follower configurations from 2 to 5 all work better than serial. The difference between *Default Validator* and *Sharing Validator* is that *Default Validator* needs to run static analysis on transactions present in a block before execution. The *Default Validator* is supposed to take more time compared to the *Sharing Validator*. However, the experiment shows no significant benefits of information sharing. The time taken by the static analysis is comparatively significantly less than expected. However, when the number of transactions per block increases to a very large, it is expected that information sharing by the miners benefits the validators.

Workload-2: In Figure 7A–C, we can observe that when the number of contract transactions decreases per block, the overall speedup increases because the contractual transaction includes the external contract method calls. Also, we can see that the speedup increases until $\frac{1}{4}$ (contract: monetary transactions) and decreases with a further decrease in the number of contract transactions per block. The experiment shows there is no significant time taken by analyzing function to gain some performance improvement over the *Sharing Validator*. Hence both *Default Validator* and *Sharing Validator* are performing almost the same.

Workload-3: As we can see in Figure C2A–C that 1 follower is performing worst due to the obvious reason of overhead of static analysis and communication with follower. Other follower configurations all outperform over serial. Also, the smaller the number of contractual transactions per block, the performance will be the better. However, there is not much performance benefit due to information sharing with the validator.

Below tables show the respective numbers for the workloads. Tables C1 and C2 show the transaction execution time while Tables C3 and C4 the respective speedup.

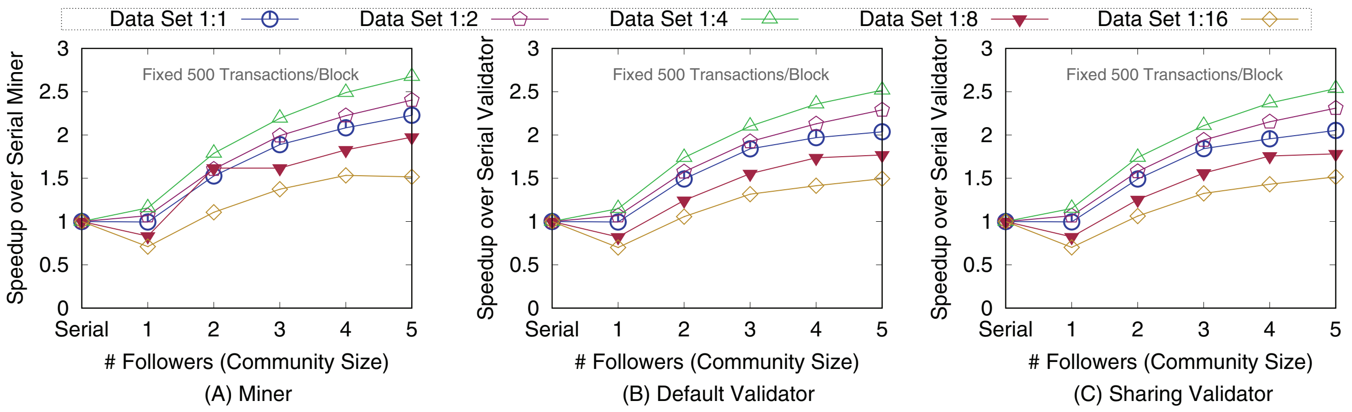

FIGURE C2 Workload-3: Average speedup by miner (omitting time to find PoW) and validator for transaction execution

TABLE C1 Workload-1: Average transaction execution time (ms) taken by miner (omitting time to find PoW) and validator

Workload 1: Execution time-averaged across data set							
Average transaction execution time (ms)			# Transactions/block				
			100	200	300	400	500
# Followers	Serial	Miner	209.18	259.68	333.51	485.55	652.95
		Validator	209.18	259.68	333.52	485.55	652.95
	1 Follower	Miner	214.93	338.60	449.45	560.49	670.04
		Default Validator	222.63	345.58	455.27	564.49	673.89
		Sharing Validator	222.77	345.3	454.88	564.66	673.29
	2 Follower	Miner	163.90	239.59	304.82	372.04	435.4
		Default Validator	175.43	250.37	315.85	384.78	449.13
		Sharing Validator	175.4	250.08	315.08	383.82	447.84
	3 Follower	Miner	145.6	202.98	255.48	305.02	352.26
		Default Validator	159.25	218.48	270.45	320.62	365.11
		Sharing Validator	159.76	218.63	269.39	319.9	363.38
	4 Follower	Miner	138.35	188.28	231.1	272.98	314.88
		Default Validator	154.81	204.33	248.87	289.15	332.95
		Sharing Validator	154.42	203.51	247.84	287.51	331.25
	5 Follower	Miner	137.79	181.98	219.57	255.97	292.88
		Default Validator	153.82	198.09	236.75	273.5	316.97
		Sharing Validator	155.58	196.92	235.71	270.3	314.15

TABLE C2 Workload-2: Average transaction execution time (ms) taken by miner (omitting time to find PoW) and validator for fixed 500 transactions per block

Workload 2: For fixed 500 transactions/block							
Average transaction execution time (ms)			ρ				
			$\frac{1}{1}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$
# Followers	Serial	Miner	899.50	803.57	745.57	467.86	348.23
		Validator	899.5	803.58	745.57	467.86	348.23
	1 Follower	Miner	903.43	752.36	643.28	561.33	489.80
		Default Validator	904.01	752.0	648.4	568.38	496.68
		Sharing Validator	903.08	752.79	647.33	567.52	495.83
	2 Follower	Miner	588.78	500.21	416.56	288.77	314.3
		Default Validator	602.82	509.83	428.58	375.17	329.25
		Sharing Validator	602.51	508.78	428.13	375.17	327.19
	3 Follower	Miner	476.16	403.2	339.78	288.77	253.37
		Default Validator	488.71	417.25	354.41	300.7	264.47
		Sharing Validator	487.99	413.73	353.36	299.27	262.56
	4 Follower	Miner	431.59	361.18	299.18	255.52	226.92
		Default Validator	456.4	377.23	316.04	268.87	246.2
		Sharing Validator	459.72	373.0	314.46	265.78	243.3
	5 Follower	Miner	403.52	334.07	278.47	236.43	211.91
		Default Validator	441.58	350.67	295.94	263.88	232.86
		Sharing Validator	437.9	347.66	293.81	261.89	229.46

TABLE C3 Workload-1: Average speedup by community miner (omitting time to find PoW) and validator

Workload-1: Execution time-averaged across data set							
Average speedup			# Transactions/block				
			100	200	300	400	500
# Followers	Serial	Miner	1	1	1	1	1
		Validator	1	1	1	1	1
	1 Follower	Miner	0.87	0.72	0.72	0.84	0.95
		Default Validator	0.84	0.71	0.71	0.84	0.95
		Sharing Validator	0.84	0.71	0.71	0.84	0.95
	2 Follower	Miner	1.15	1.02	1.07	1.27	1.47
		Default Validator	1.07	0.98	1.03	1.23	1.42
		Sharing Validator	1.07	0.98	1.03	1.23	1.42
	3 Follower	Miner	1.29	1.21	1.27	1.55	1.81
		Default Validator	1.18	1.12	1.20	1.47	1.75
		Sharing Validator	1.17	1.12	1.20	1.48	1.75
	4 Follower	Miner	1.37	1.30	1.41	1.73	2.03
		Default Validator	1.28	1.2	1.3	1.64	1.92
		Sharing Validator	1.22	1.2	1.31	1.65	1.93
	5 Follower	Miner	1.39	1.35	1.48	1.85	2.18
		Default Validator	1.25	1.24	1.37	1.73	2.022
		Sharing Validator	1.24	1.24	1.38	1.78	2.04

TABLE C4 Workload-2: Average speedup by community miner (omitting time to find PoW) and validator

Workload-2: For fixed 500 transactions/block							
			ρ				
Average speedup			$\frac{1}{1}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$
# Followers	Serial	Miner	1	1	1	1	1
		Validator	1	1	1	1	1
	1 Follower	Miner	0.99	1.07	1.16	0.83	0.71
		Default Validator	0.99	1.07	1.15	0.82	0.7
		Sharing Validator	0.99	1.07	1.15	0.82	0.7
	2 Follower	Miner	1.53	1.6	1.79	1.31	1.11
		Default Validator	1.49	1.57	1.74	1.24	1.06
		Sharing Validator	1.49	1.58	1.74	1.25	1.06
	3 Follower	Miner	1.88	1.99	2.19	1.62	1.37
		Default Validator	1.84	1.92	2.1	1.55	1.32
		Sharing Validator	1.84	1.94	2.12	1.56	1.32
	4 Follower	Miner	2.08	2.22	2.49	1.83	1.53
		Default Validator	1.97	2.13	2.36	1.74	1.41
		Sharing Validator	1.96	2.15	2.37	1.76	1.43
	5 Follower	Miner	2.23	2.4	2.67	1.97	1.64
		Default Validator	2.04	2.29	2.52	1.77	1.49
		Sharing Validator	2.05	2.31	2.54	1.78	1.52

APPENDIX D. END-TO-END BLOCK CREATION TIME

This section presents the analysis for the end-to-end block creation time, including time to find PoW at the miner for transaction varies from 100 to 500 in Workload-1. At the same time, it is fixed to 500 in Workload-2 and Workload-3 however, other parameters as data set and community size vary, respectively.

D.1 Transaction execution time analysis

Figure 8A shows the line plots for mean end-to-end block creation time taken by the miner (including time to find PoW) for Workload-1. The overhead of static analysis and communication is negligible, including time to find PoW. Here, all follower configurations are performing better than serial. Since the PoW is a random nonce for which the block's hash is less than the given difficulty, it can take a variable amount of time to find nonce. Also, the serial and follower configurations have different orders of transactions in the final block. Both blocks are correct as proposed by the miner and considered as the final order of transaction execution. It is possible that some outliers in serial execution resulted in a higher mean for the end-to-end time required to create a block than one follower. Another observation is that the time required to create a block increases linearly as the number of transactions per block increases. Across the different numbers of transactions, the trend remains consistent with followers; the higher number of followers takes less time than the less number of followers.

For Workload-2 results are shown in Figure 8B. The reason for the serial and one follower for these plots remains the same as explained above. The time required to create blocks across different data sets varies and does not show any pattern based on a contract to monetary transaction ratio. Since it largely depends on the PoW search. With PoW, we always guarantee that when the number of followers increases, it will take less time to create a block (including time to find PoW) than the serial.

Similarly, in Workload-3 when the number of transactions per block is fixed to 500 and community size increases (i.e., followers in the community increases), the time taken to mine a block always takes lesser time than the serial and smaller size community. Figure D1 confirms this observation; however, it is challenging to claim which data set is doing better than others, and the reason is that mining time dominates the transaction execution time.

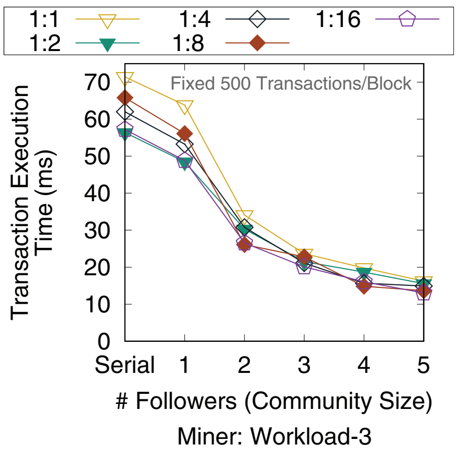

FIGURE D1 Workload-3: Average end-to-end block creation time by miner including time to find PoW

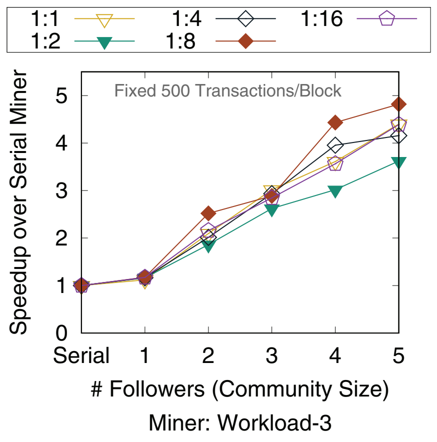

FIGURE D2 Workload-3: Average end-to-end block creation speedup by community miner over serial miner including time to find PoW

D.2 Speedup analysis

For Workload-1, Figure 9A shows the mean speedup achieved by the parallel community-based miner over the serial miner (including time to find PoW). Here, all follower configurations are achieving better speedups than serial. The observation here is that the speedup varies as the number of transactions per block increases. Across the different numbers of transactions, the trend remains consistent with followers; the higher the number of followers , the higher the speedup.

Figure 9B shows the line plots for the mean speedup achieved over serial by the parallel miner, including time to find PoW for Workload-2. The time required to create blocks across different data sets varies and does not show any pattern based on transaction ratio (i.e., contractual vs momentary transactions). Since it largely depends on the PoW search. With PoW, we always guarantee that more followers will give higher speedups over serial, including time to find PoW. In Workload-3 the speedup increases with an increase in the size of the community (Figure D2). However, there are no fixed pattern with varying transaction ratios.

APPENDIX E. RESULTS AND ANALYSIS WHEN NUMBER OF TRANSACTION VARIES FROM 500 TO 2500 PER BLOCK

This section includes the experiments done on a varying number of transactions, from 500 to 2500 per block. Similar to the earlier experiments, where transactions per block varied from 100 to 500, this experiment for Workload-1 transactions varies from 500 to 2500. The speedup is averaged over varying the contract to monetary transaction ratio ρ (i.e., from $\frac{1}{1}$ to $\frac{1}{16}$). In Workload-2 ρ varies from $\frac{1}{1}$ to $\frac{1}{16}$ while the number of transactions per block remains fixed at 2500. While in Workload-3, community size varies from 1 follower up to 5 followers, and the number of transactions per block remains fixed to 2500. In all the figures, serial execution served as a baseline.

E.1 Transaction execution time analysis

Workload-1: Figure E1 shows the average transaction execution time taken by the miner and validator. As shown in Figures E1A–C, the time required to execute transactions per block increases as the number of transactions increases in the block. Also, the one follower performs the worst due to the overhead of static analysis and communication with the leader. Other follower configurations from 2 to 5 are all better than serial. The difference between *Default Validator* and *Sharing Validator* validators is that *Default Validator* needs to run static analysis on block transactions before execution. The *Default Validator* is supposed to take more time compared to the *Sharing Validator*. The experiment shows a slight performance improvement for the *Sharing Validator* over the *Default Validator* as the execution time. It is significant enough to see the difference.

Workload-2: In this workload, the number of transactions per block is fixed at 2500, while the contract to monetary transaction ratio ρ varies from $\frac{1}{1}$ to $\frac{1}{16}$. In Figure E2A–C, it can be seen that by decreasing the number of contract transactions than monetary transactions per block, the overall time required to execute transactions also decreases because a contractual transaction includes the external calls. Further, it can be noticed that serial execution outperforms the one follower configuration due to the static analysis and communication overhead associated with the one follower configuration. Although, other configurations (2–5 followers in the community) outperform serial execution with the increase in the number of followers in the community. However, with the increase of monetary transactions in the block, serial execution started giving better performance because communication dominates the transaction execution. These figures show that the time required to execute more transactions per block decreases as the number of contract transactions decreases. The parallel validator always takes less time than the serial one, and we can also observe a significant gap as we increase the number of monetary transactions per block. The *Sharing Validator* achieved a slight improvement over the *Default Validator*, very close to each other.

Workload-3: Figure E3 shows the analysis for a fixed number of transactions (2500) per block with varying community size. Here we see how the transaction ratio in each block will have an impact on the performance. We can observe in Figure E3A–C that 1 follower is performing the worst due to the overhead of static analysis and communication with the leader. Other follower configurations from 2 to 5 work better than serial, and

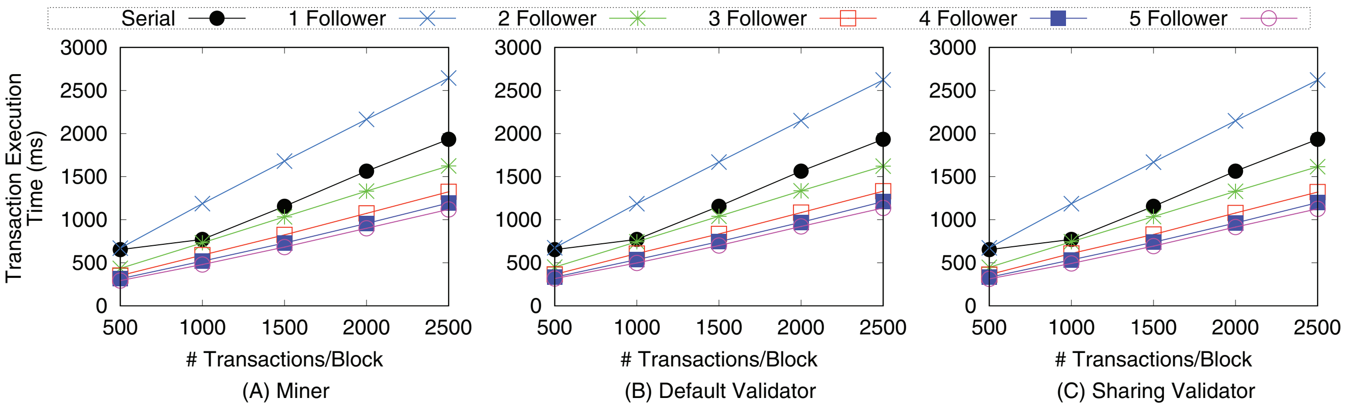

FIGURE E1 Workload 1: Average transaction execution time by miner (omitting time to find PoW) and validator when transactions varies from 500 to 2500 per block

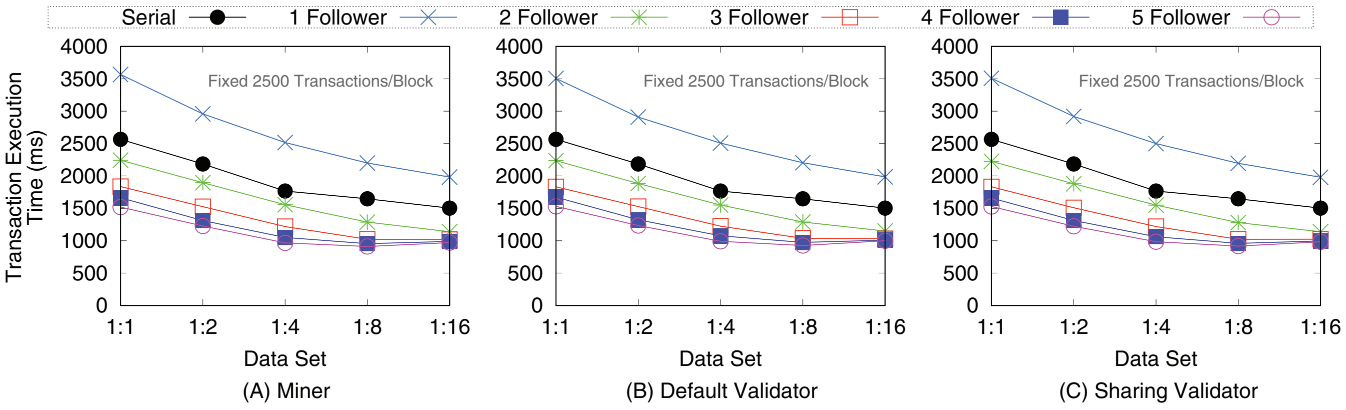

FIGURE E2 Workload 2: Average transaction execution time by miner (omitting time to find PoW) and validator for 2500 transactions per block

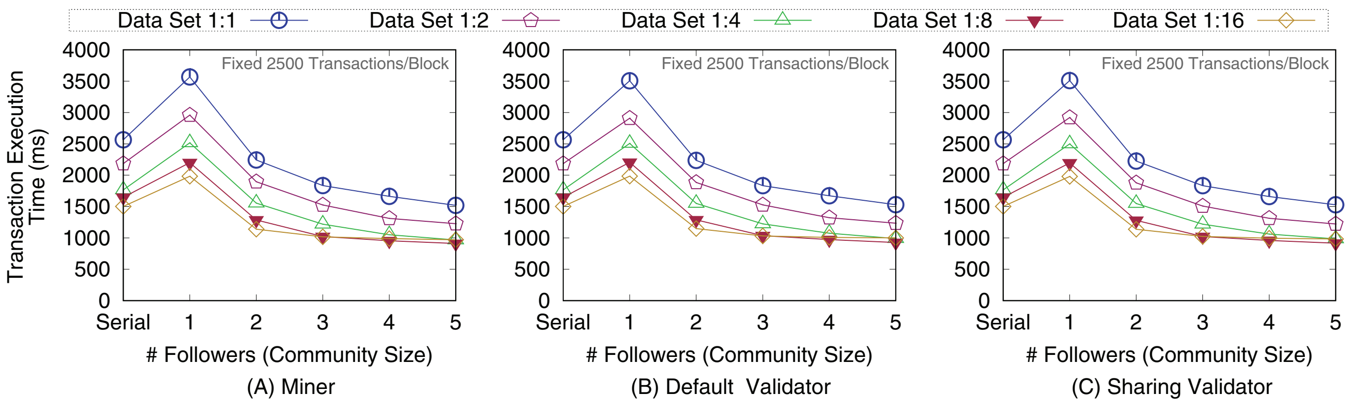

FIGURE E3 Workload 3: Average transaction execution time by miner (omitting time to find PoW) and validator for 2500 transactions per block

execution time decreases as the number of followers increases. Also, the smaller the number of contractual transactions per block, the performance will be better, that is, $\frac{1}{1}$ is taking higher time than $\frac{1}{2}$ and $\frac{1}{16}$ is taking least time among them since it consists of 16× more monetary transactions than contractual transactions in a block. We can see the slight performance difference in the *Sharing Validator* and the *Default Validator*.

E.2 Speedup analysis

Workload-1: Figure E4 shows the mean speedup obtained by the parallel miner (omitting time to find PoW) and validator over the serial miner and validator. As shown in Figure E4, the mean speedup increases as the number of transactions per block increases, but the serial is outperforming one follower configuration of community-based parallel execution. This happens due to the static analysis and communication overhead associated with the leader and one follower communication. While in other settings, that is, 2–5 followers in the community, all achieving better speedup over serial. Also, there is a drop in speedup going from 500 to 1000, but there is a steady increase in speedup. The *Default Validator* and *Sharing Validator* are outperforming serial.

Workload-2: In this workload, we fixed the number of transactions per block to 2500. However, the contract to monetary transaction ratio ρ varies from $\frac{1}{1}$ to $\frac{1}{16}$, that is, contractual to monetary transaction ratio varies. In Figures E5A–C, it can be observed that by varying the ratio of contractual to monetary transactions the overall speedup increases because contractual transactions drops with the increase in monetary transactions per block. Further, we can observe that speedup increases till $\frac{1}{8}$ and then decreases with a further decrease in the number of contract transactions per block. There is a slight performance improvement in the *Sharing Validator* over the *Default Validator*.

Workload-3: Figure E6 shows that one follower is performing worst due to the overhead of static analysis and communication. Other follower configurations from 2 to 5 are all doing better than serial, and speedup increases as the number of followers increases. Also, the smaller the number of contractual transactions per block, the better the performance will be. This is because of the external method called by the contractual transactions, as explained in the Workload-2.

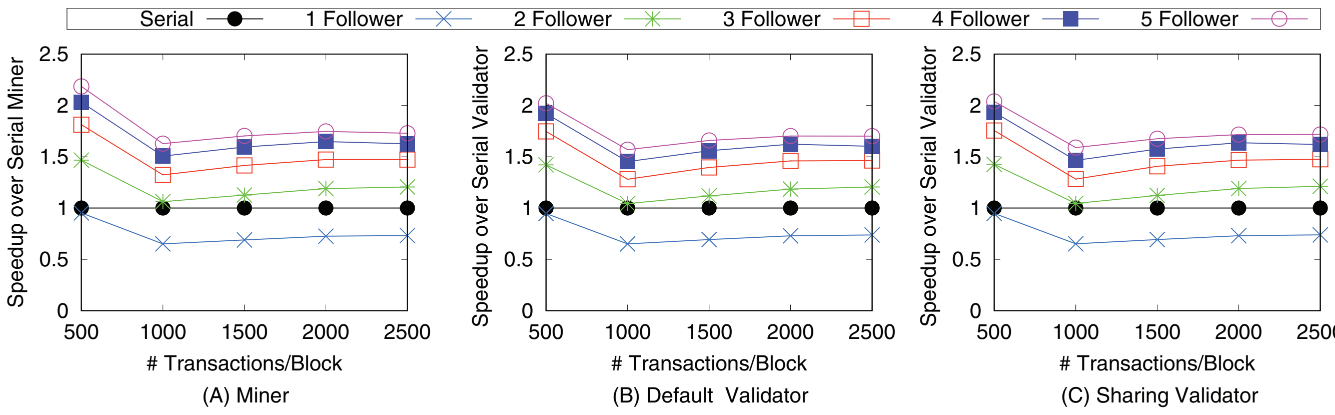

FIGURE E4 Workload 1: Average speedup by community miner (omitting time to find PoW) and validator for transaction execution when transactions varies from 500 to 2500 per block

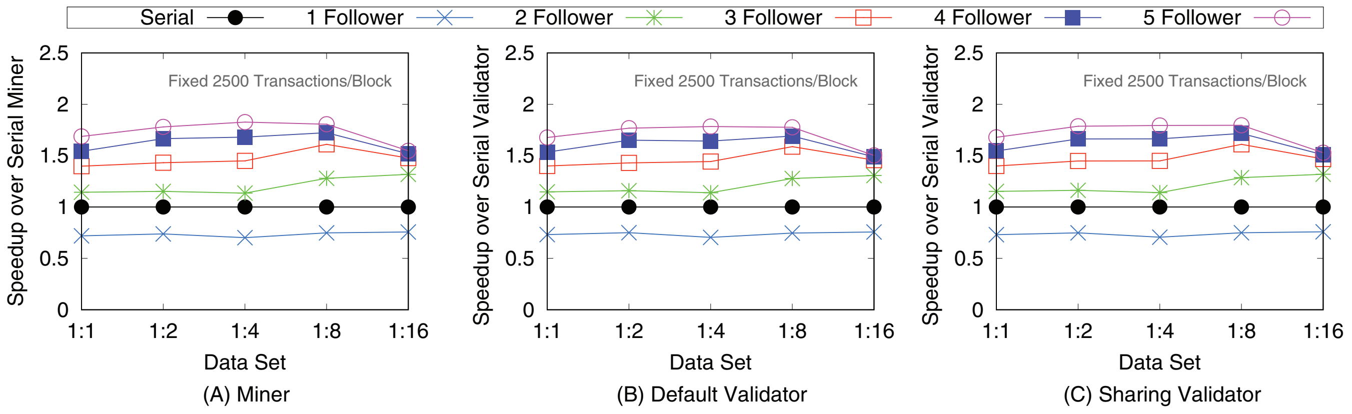

FIGURE E5 Workload 2: Average speedup by community miner (omitting time to find PoW) and validator for transaction execution for 2500 transactions per block

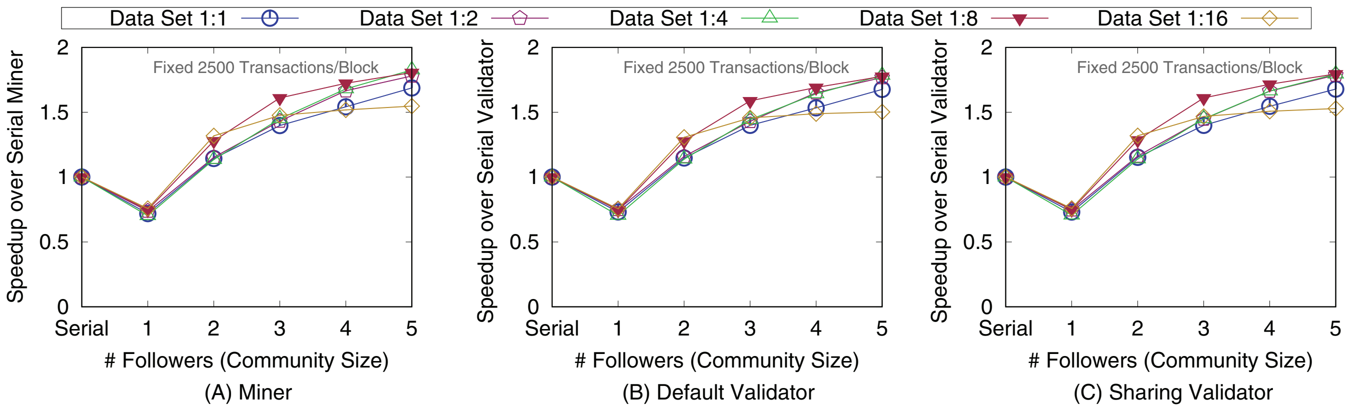

FIGURE E6 Workload 3: Average speedup by community miner (omitting time to find PoW) and validator for transaction execution for 2500 transactions per block