Abstract—Sharding is a promising blockchain scaling solution. But it currently suffers from high latency and low throughput when it comes to cross-shard transactions, i.e., transactions that require coordination from multiple shards. The root cause of these limitations arise from the use of the classic two-phase commit protocol, which involves locking assets for extended periods of time. This paper presents RIVET, a new paradigm for blockchain sharding that achieves lower latency and higher throughput for cross-shard transactions. RIVET has a single reference shard running consensus, and multiple worker shards maintaining disjoint states and processing a subset of transactions in the system. RIVET obviates the need for consensus within each worker shard, and as a result, tolerates more failures within a shard and lowers communication overhead. We prove the correctness and security of RIVET. We also propose a more realistic framework for evaluating sharded blockchains by creating a benchmark based on real Ethereum transactions. An evaluation of our prototype implementation of RIVET and the baseline 2PC, atop 50+ AWS EC2 instances, using our evaluation framework demonstrates the latency and throughput improvements for cross-shard transactions.

I. INTRODUCTION

A typical blockchain system replicates storage and computations among all its nodes and runs a single consensus algorithm involving all nodes [1], [2]. Such a global replication approach has limited scalability and throughput. Sharding has emerged as a promising approach to address the long-standing quest for blockchain scalability [3]–[8]. Sharding improves scalability by partitioning different responsibilities and resources to different sets of nodes. A sharded blockchain can potentially shard its storage, communication, and computation.

A critical design component of a sharded ecosystem is its mechanism to handle cross-shard transactions, i.e., transactions that involve more than one shards. Cross-shard transactions are essential to sharded blockchains as they enable users to atomically interact with multiple shards; a sharded blockchain without such support is uninteresting as it degenerates to running multiple independent blockchains. Popular examples of cross-shard transactions include atomic exchange of assets maintained at different shards [9], and atomically book a flight ticket and a hotel room where the two are being sold in different shards [10], [11].

A number of prior works [3]–[8] proposed sharding schemes under different settings. These protocols can linearly scale intra-shard transactions, i.e., transactions that can be processed within a single shard, by adding more shards to the system. However, existing works have several limitations when it comes to cross-shard transactions. Firstly, all of the above works adopt the two-phase commit (2PC) protocol to execute cross-shard transactions. While 2PC is the simplest and most well-known atomic commit protocol, it requires nodes to lock assets for an extended period of time, leading to higher latency and lower throughput for cross-shard transactions. Secondly, they primarily focus on the Unspent Transaction Output (UTXO) [1] transaction model rather than the general-purpose smart contract and key-value store model. Thirdly, the evaluation methodology of existing works is ad-hoc and artificial. In particular, most of them randomly allocate unspent transactions to shards and test the system with randomly generated transactions. Clearly, such a random allocation would result in the vast majority of transactions becoming cross-shard transactions and would fail to capture the characteristics of a realistic sharded blockchain, thereby raising doubts on the accuracy of the evaluation results.

In this paper, we aim to address the above limitations from several aspects as we elaborate below.

A new paradigm for cross-shard transactions. We present a new framework for sharded blockchains called RIVET. RIVET partitions storage, communication, and computations among its nodes, and supports the generic smart contract execution model. RIVET achieves lower confirmation latency and better throughput for cross-shard transactions. We give an overview of RIVET below.

RIVET has a single reference shard and multiple worker shards. Each shard can be both permissioned and permissionless. This paper focuses on the permissioned setting. The reference shard runs a consensus layer and maintains its own blockchain. Each worker shard maintains a disjoint set of states in the system. Each worker shard executes transactions involving it and vouches for the validity of the resulting state. It is important to note that worker shards do not provide consensus or finalize these blocks – instead, they periodically submit hash digests of worker blocks to the reference shard. Cross-shard transactions are also submitted to the reference shard by users in the system. The worker shard commitments and cross-shard transactions are then finalized and ordered by the consensus layer of the reference shard. When a set of cross-shard transactions are finalized, each worker shard locally executes the subset of these transactions that are relevant to it, atop the latest committed states. To do that, a worker shard needs to download the data needed by these transactions from
other shards along with accompanying proofs showing the validity of the data (under the latest commitments).

RIVET offers two main advantages over the classic 2PC approach. The first advantage is that worker shards do not need to run a consensus protocol. As a result, each worker shard in RIVET requires few replicas\(^1\) runs a simpler and cheaper (using less communication) protocol, compared to the 2PC approach. The second advantage of RIVET is that cross-shard transactions have a better confirmation latency. Specifically, a cross-shard transaction gets confirmed as soon a single worker shard involved in the transaction locally executes it and adds it to a certified worker block (§IV). This holds independent of the number of shards involved, and is in sharp contrast to the 2PC approach, where cross-shard transactions are delayed by the slowest participating shards. As a consequence of the lower latency, cross-shard transactions in RIVET lock data items for a shorter amount of time (i.e., they are made available to future transactions sooner), leading to higher throughput for cross-shard transactions.

Not running a consensus protocol in worker shards also comes with a downside: intra-shard transactions are finalized only when the state commitment of the block (or a successor block) gets included in the reference chain. This means RIVET will have a higher latency for intra-shard transactions compared to 2PC and occasionally have to discard some certified (see details in §IV).

**Evaluation framework for sharded blockchains.** We characterize the behavior of sharded blockchains with the aim of better understanding interactions within and across shards based on the Ethereum transaction history. We proceed to create a realistic evaluation benchmark for sharded blockchains. At a high level, our benchmark represents interactions between accounts as a graph and partitions them into different shards while minimizing the amount of cross-shard transactions. Overall, we observe less than 30% cross-shard transactions among different shards as opposed to over 90% cross-shard transactions arising from a random allocation of accounts to shards [6, 7]. We analyze our results and see that our approach partitions major services along with their popular users into different shards. Thus we think that the benchmark we create is realistic, and is a great way to evaluate sharded systems, both ours and future ones.

**Experimental Evaluation.** We implement both RIVET and 2PC atop open-source Quorum client [12]. We then evaluate them using our benchmark on a testbed of 50+ AWS EC2 instances with realistic network delays. Our evaluation illustrates (§VI) that most all cross-shard transactions in RIVET are confirmed within a worker block interval from its inclusion in the reference chain. Furthermore, RIVET has approximately 75% reference block utilization in comparison to 50% utilization of 2PC based design. Also, in most scenarios (> 99%) state variables accessed by cross-shard transactions are unlocked immediately in RIVET whereas they remain locked for at least one reference block interval in 2PC.

In summary, we make the following contributions:

- We present RIVET, a novel sharded system that has lower confirmation latency for cross-shard transactions, tolerates more failures, and has better block utilization over existing approaches. We supplement our claims with theoretical proofs of their correctness and security.
- We analyze historical Ethereum transactions to better characterize benefits of sharding in permissionless blockchains and use our analysis to create a realistic benchmark for evaluating sharded blockchains.
- We implement both RIVET and 2PC atop an open source Quorum client and rigorously evaluate them using our benchmark on a testbed of 50+ AWS EC2 instances. Our evaluations further corroborate our design choices.

**Paper Organization.** In §II we describe the necessary background. We next describe the methodology we employ to analyze Ethereum transaction history and our findings in §III. This is followed by the detailed design of RIVET in §IV. We theoretically prove correctness and security of RIVET in §V. §VI describes our prototype implementation of RIVET and 2PC, experimental setup and observations from experimental results. We describe the related work in §VII and end with a discussion on future research directions in §VIII.

**II. BACKGROUND**

**A. Blockchain Sharding and Cross-shard Transactions**

In existing sharded blockchain proposals, each shard runs its own blockchain and maintains a disjoint portion of the global state. Sharding is expected to improve performance because, hopefully, most transactions are “local” to a single shard and only require the participation of replicas maintaining that shard. We call these transactions intra-shard transactions. Transctions that involve multiple shards are called cross-shard transactions. Execution of cross-shard transactions require some coordination mechanism among the participating shards. Most existing sharding schemes use 2PC to atomically execute cross-shard transactions. Moreover, they primarily focus on UTXO based model where each transaction uses unspent tokens as inputs to create a new transaction with fresh unspent outputs. We use an example to illustrate how such a sharding system works.

Say a user creates a cross-shard transaction that takes two unspent tokens, \(u_1\) on a shard \(X_1\) and \(u_2\) on a second shard \(X_2\), and moves them to a third shard \(X_3\). The creator of the transaction, referred to as the client, broadcasts this transaction to the two input shards \(X_1\) and \(X_2\). On receiving this transaction, the two input shards first validate it, i.e., check whether the tokens are indeed unspent; if so, an input shard locks the input and produces an approval certificate (e.g., signed by sufficiently many replicas within the shard) confirming the validity of the input. On the contrary, say one of the inputs is invalid, e.g., the associated token has already been spent, the corresponding input shard produces a rejection.

\(^1\)We use the terms replica and node interchangeably in this paper.
certificates indicating the invalidity of the input. This is the first (locking) phase in classic 2PC. Note that once an input is locked, no future transaction can use the input until it is unlocked.

The client waits for the certificates from all input shards, and if all input shards unanimously approve the transaction, it sends the transaction along with all the certificates to the output shard(s) \( (X_3 \text{ in our example}) \). On receiving the cross-shard transaction and the unanimous approval certificates, the output shard adds the desired token to the appropriate account and sends a confirmation certificate to the client. Alternatively, if any of the input shards reject its input, every output shard rejects the transaction. The client also forwards the approval or rejection certificates to every input shard. An input shard marks the input as spent if there are unanimous approval certificates, or else unlocks the input for future transactions. This is the second phase of the standard 2PC protocol.

B. Smart Contracts and Transactions

Smart contracts are programs consisting of a set of functions that are identified by unique addresses. Each smart contract maintains its state, a set of disjoint key-value pairs, that can be modified according to the program logic of the contract. Smart contracts are created by sending transactions containing its code. Upon creation, users can invoke functions in them by sending transactions to the contract address. Functions of smart contracts can also be invoked by other smart contracts.

A transaction invokes a function by specifying the appropriate contract address, the function, and the required arguments to the function. On receiving a transaction, the proposer of a block validates the transaction before including it in its proposal. Once included in a proposal, transactions are executed atop some initial state, and its execution results in a new state. The state transition is deterministic and is denoted by the function \( \Pi \). Specifically, let state be the initial state. Then the resulting state after executing a transaction \( tx \) is \( \text{state}' = \Pi(\text{state},tx) \). Sometimes, we overload the notation to apply the transition function \( \Pi \) on an ordered list of transactions.

III. A Benchmark for Sharded Blockchains

Prior sharding works partition the state among shards in a uniformly random manner. Clearly, such a random partitioning does not capture a realistic workload for sharded blockchains. In particular, it will result in a dominant fraction of cross-shard transactions \[ 6, 7 \]. Evaluation results from these contrived benchmarks may significantly depart from reality and fail to accurately reflect the performance of sharded blockchains.

In this section, we seek to create a benchmark suitable for sharded blockchains by intelligently partitioning the workload of Ethereum, which is a leading blockchain supporting general computation in the real world.

To this end, we partition the Ethereum state in such a way that cross-shard interactions are minimized. We analyze our results, and observe that major "services" are assigned to different shards. Moreover, many other accounts interact with one major service frequently and they are assigned to the same shard as that service. We believe this will be close to the ecosystem of a realistic sharded blockchain and the benchmark created this way is a good candidate for evaluating sharded blockchains in this paper as well as future works.

A. Methodology

We take four thousand different blocks starting approximately at the 7.3 million \( \text{th} \) block. We represent accounts and transactions interaction with them as an undirected graph. Each account is a vertex. Edge weights denote the number of transactions that involve the corresponding two accounts. In particular, for every transaction that involves accounts \( u \) and \( v \) both, the edge weight of \( (u,v) \) is incremented by one. If a transaction involves more than two accounts, it contributes one unit of weight to all edges in the clique formed by these accounts.

Our partitioning scheme is inspired by techniques used in distributed database partitioning. The connection will be explored in section \[ VII \]. As mentioned, we hope to partition the accounts into a number of disjoint shards and minimize the number of cross-shard transactions. But, a blunt partitioning approach will simply put all accounts in a single shard and eliminate cross-shard transactions. Thus, we need additional constraints to avoid the above trivial partition results. To this end, we require the partition to be more or less balanced in terms of activities. In particular, we will assign every vertex four different weights: (1) the account’s storage size (measured in bytes) (2) the total degree of the vertex, i.e., the total number of transactions that access the vertex, (3) the total amount of computation (measured in gas) used by the transactions accessing the account, and (4) the total size of the transactions accessing the account. These four weights measure the storage, frequency of involvement, computation, and communication associated with an account, respectively.

We then seek to partition the graph into non-overlapping shards such that the total weight of the cross-shard edges are minimized (i.e. a min-cut) and all shards are balanced within a constant factor in terms of each of the four aggregated weights. For each of the four metrics (storage, number of involvement, computation, and communication), the aggregated weight of a shard is the sum of the corresponding weights of the vertices assigned to the shard. We use the Metis tool \[ 13 \] – a heuristic tool for constrained \( k \)-way graph partitioning – to perform the partitioning for different values of \( k \).

Figure 1 illustrates our approach on a sample state with eight accounts \( \{a_1, \ldots, a_8\} \) and six transactions \( \{tx_1, \ldots, tx_6\} \) indicated by the colored regions. Accounts accessed by the transaction are enclosed by their respective regions. For example, transaction \( tx_5 \) accesses \( a_6, a_7 \) and \( a_8 \). Account \( a_4 \) is accessed by \( tx_2, tx_3 \) and \( tx_4 \). Edge weights between a pair of nodes represent the number of times the pair has been accessed by common transactions. For example, edge \( (a_6, a_7) \) has a weight of 2 as the pair has been accessed by both \( tx_4 \) and \( tx_6 \). Also, the aggregated weights of accounts in both partition are balanced.
can be modified according to the program logic of the contract.
Smart contracts are created by sending transaction requests using the `deploy` function.
These transactions are verified and added to the Ethereum blockchain, following which they become
valid. These transactions are executed by virtual machines running on every node in a network of
peer-to-peer nodes. Each node contains a local copy of the blockchain. Transactions are processed
asynchronously, and miners compete to add blocks containing verified transactions to the
blockchain. Once added, the transaction is confirmed if it includes the transaction in its proposal. Once
the proposer of a block validates the transaction, and on successful validation, the transaction is
confirmed on the blockchain.

### Sharding Approach

Sharding is a technique used to create multiple shards, or databases, for a blockchain. In this
approach, we will employ a scheme that achieves this desiderata based on the analysis of
historical Ethereum transactions. We affirmatively answer this question and present a concrete
approach that achieves this desiderata.

#### Validation Protocol

To validate the fraction of cross-shard transactions, we use a simple validation protocol. For
example, all the accounts of a popular cryptocurrency exchange Binance [14], are assigned to shard
X, while other edge weights denote the fraction of transactions (out of all transactions in the system)
involving those two shards. Figure 3 illustrates the fraction of cross-shard transactions in obtained
partition with six worker shards X_1 to X_6. Self-edge weights denote the fraction of intra-shard
transactions (out of all transactions in the system), while other edge weights denote the fraction of
transactions (out of all transactions in the system) involving those two shards.

#### Intra-shard and cross-shard activities

Intra-shard activities are those that occur within a single shard, while cross-shard activities
involve the exchange of information between different shards. The state is divided into shards in
order to balance the workload and improve performance. The number of shards is determined by
the number of worker shards, k.

#### Data transfer between shards

Worker shards need to download data from other worker shards to execute cross-shard
transactions. Figure 4 illustrates the cumulative distribution of cross-shard transactions in terms of
the amount of data transfer needed. Observe that, in every worker shard, more than 95% of
cross-shard transactions only require transferring at most 128 bytes of data (4 values) from other
shards to execute the transaction locally. This shows that the data transfers for local execution of
cross-shard transactions is minimal.

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**Table I: Average fraction of cross-shard transactions with varying number of shards, k, evaluated by partitioning a trace of approximately 750 thousand historical Ethereum transactions. The average is taken over 5 different ranges of 1000 blocks each.**

| #Shards | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|---------|----|----|----|----|----|----|----|
| Cross-shard | 0.11 | 0.17 | 0.14 | 0.18 | 0.18 | 0.17 | 0.16 |

Fig. 1: Sample graph with eight accounts \{a_1, \ldots, a_8\} and six transactions \{tx_1, \ldots, tx_6\} marked with regions of different colors. Vertex weights is a four element tuple (degree, state size, gas usage, transaction size).

Fig. 2: Average fraction of transactions that are cross-shard with varying number of shards, k, evaluated by partitioning a trace of approximately 750 thousand historical Ethereum transactions. The average is taken over 5 different ranges of 1000 blocks each.

Fig. 3: Fraction of intra-shard and cross-shard transactions in obtained partition with six worker shards X_1 to X_6. Self-edge weights denote the fraction of intra-shard transactions (out of all transactions in the system), while other edge weights denote the fraction of transactions (out of all transactions in the system) involving those two shards.

Fig. 4: Cumulative fraction of cross-shard transactions in all the six shards in terms of data downloaded from other shards (in bytes).
Potential gaps from future sharded blockchains. Despite our efforts to mimic realistic workloads, we would like to acknowledge the potential gap between our workload and real-world sharded blockchains (when they come into existence). Since cross-shard transactions are inherently more expensive (involve locking and data transfer between shards), users may take intelligent measures to reduce the amount of cross-shard transactions they use. For example, a user who repeatedly uses a service from a shard other than his home shard may decide to create accounts in that other shard and transfer some tokens to it. Further, applications or contracts that expect to reduce conflicts between different transactions. These behaviors and practices may lead to a further reduction in cross-shard transactions in comparison to our benchmark. Lastly, the dominating activities on the Ethereum blockchain (and other blockchains) today come from trading, exchanges, and mining pools. This will likely change if blockchains are to find more practical applications. It is hard to predict what applications will prevail and what characteristics (related to sharding) they will exhibit. The methodology in this section represents our best effort in creating a sharded blockchain workload given the data available at the time of writing.

IV. RIVET Design

A. Overview

In RIVET there are \( k + 1 \) shards \( \{ X_0, X_1, \ldots, X_k \} \) in total. Shard \( X_0 \) is referred to as the reference shard and runs a fault tolerant consensus protocol. All cross-shard transactions in RIVET are included and ordered by the reference shard. The other \( k \) shards are called worker shards, and they maintain disjoint subsets of the system states. The worker shards verify and prove the validity of its state; but they do not need to provide consensus. This paper focuses on the permissioned setting\(^3\). We adopt the widely used partial synchrony timing model, that is, RIVET ensures safety (consistency) even under asynchrony, and provides liveness only during periods of synchrony. We assume there can be up to \( f \) Byzantine nodes in each shard. The reference shard uses a Byzantine Fault Tolerant (BFT) consensus protocol for the partial synchrony model, which has \( 3f + 1 \) replicas. Each worker shard has \( 2f + 1 \) replicas. We will give a more formal treatment of the model and its guarantees in IV.6.

Each worker shard maintains a sequence of certified blocks where each block includes some intra-shard transactions and a hash of its predecessor. We refer to this sequence of blocks as the worker chain. Replicas within a worker shard append certified blocks to the worker chain by collecting at least \( f + 1 \) distinct signatures from replicas within the shard. Once a block is certified, the worker shard submits the cryptographic digest of the resulting state to the reference chain, to be finalized by the reference shard. We note again that, instead of running a consensus protocol per worker shard, RIVET only requires worker shards to certify the validity of worker blocks per the protocol specification (see IV-D for precise definition of valid blocks). A worker block is finalized when a reference block containing its commitment is finalized in the reference chain.

Figure 5 illustrates the high-level idea behind RIVET with an example. Say a user creates a cross-shard transaction \( ctx \) that involves two shard \( X_a \) and \( X_b \). Let \( state_{a_0} \) and \( state_{b_0} \) be the latest committed states from \( X_a \) and \( X_b \) respectively. Also, let \( tx_1 \) and \( tx_2 \) be two intra-shard transactions. Here, \( ctx \) is first included in block \( P_i \) by the reference shard; then replicas in \( X_a \) and \( X_b \) execute \( ctx \) atop the latest committed states \( state_{a_0} \) and \( state_{b_0} \). After executing \( ctx \), both shards independently execute some intra-shard transactions, e.g., \( X_a \) executes \( tx_1 \) and \( X_b \) executes \( tx_2 \), and update their commitments of the latest execution results \( state_{a_1} \) and \( state_{b_1} \).

A careful reader may note that the core approach in RIVET can be viewed as a locking scheme. At every state commitment, each shard implicitly locks its entire state to potential future cross-shard transactions. However, despite locking the state, a worker shard optimistically proceeds to execute and certify new intra-shard transactions atop the locked state, hoping that no conflicting cross-shard transactions will appear in the reference chain before they commit the updated state. If indeed no cross-shard transactions involving a worker shard appear in the reference chain, the new state commitment gets added to the reference chain and the worker shard makes progress. On the other hand, if some conflicting cross-shard transactions appear before the next state commitment, RIVET forces worker shards to execute those cross-shard transactions first before any new intra-shard transactions. In doing so, a worker shard may have to discard some certified blocks from its worker chain. We report statistics on how often a worker shard has to discard its certified blocks in VI.

It is also important to note that every worker shard can independently execute cross-shard transactions as soon as it notices them in a finalized reference block. This holds independent of the status quo of other involved shards. This is in sharp contrast to 2PC where each shard waits for every other shard specified in the transaction to lock its state first, and only then proceeds to execute the cross-shard transaction atop the locked states. Indeed, this very nature of pro-active state commitments allows RIVET to execute cross-shard transactions more efficiently than 2PC.

B. Data structures

Worker shard blocks. A certified worker block \( B_i \) at height \( i \) at shard \( X_a \) consists of the following components

\[
B_i = \langle \text{hash}_{i-1}, r_i, \text{state}_i, Q^{(a)}_i, T_i \rangle
\]

(1)

Here, \( \text{hash}_{i-1} \) is the hash of the parent block, \( r_i \) is the height of the latest known reference block, \( Q^{(a)}_i \) is the ordered list of cross-shard transactions that are included in the reference block since the last commitment from \( X_a \) to height \( r_i \) (both

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\(^3\)It is conceivable to have (some or all) shards to be permissionless by running a permissionless blockchain per shard. We leave this direction as future work.
intra-shard transaction. Similar to transactions in an unsharded system, intra-shard transactions in RIVET specify the identity of the function they wish to invoke and appropriate function parameters. Creators of intra-shard transactions send these transactions to replicas of the worker shard storing the state required for their execution. Respective worker shard replicas then gossip the transactions among themselves and include it in the next available worker block.

Cross-shard transaction. In addition to information specified in every intra-shard transactions, every cross-shard transaction also specifies its potential read-write set in its description. The creator of every cross-shard transactions use ideas akin to Optimistic Lock Location Prediction (OLLPP) [17] to generate the read-write set. We include the read-write set in the description of the cross-shard transaction to indicate the subset of shards necessary for executing the transaction along with the keys these shards need to exchange for its execution. Also, unlike intra-shard transactions, creators of every cross-shard transaction send their transaction directly to at least one honest replica of the reference shard. These replicas then gossip these transactions among themselves and include them in new reference blocks as described in the next section.

C. Reference Shard Protocol

Replicas in the reference shard run a standard consensus protocol, such as PBFT [18], HotStuff [19], to finalize new proposed blocks and append them to the reference chain. Hence, in this section, we primarily focus on the rules for proposing a new block. As in HotStuff, we use views with one leader, also referred to as the proposer, per view. Also, in every view, the leader of the view is responsible for driving the consensus on newer blocks. Let $L$ be the proposer of the current view. To propose a new reference block $P_r$ at height $r$, $L$ includes a subset of valid block commitments and cross-shard transactions. In $P_r$, the state commitments of worker shards are ordered before the cross-shard transactions, and they are chosen as follows.

Let $X$ be a shard with commitment $\text{com}_l$ with state $\text{state}_l$ for block $B_l$ as its latest commit that appears in reference chain up to the parent block of the proposal $P_r$. Let $\text{com}_l$ appear in reference block $P_s$. Then, a new of commitment $\text{com}_j = \langle \text{state}_j, H_j \rangle$
Fig. 6: Illustration of valid (com_i) and invalid (com_j) block commitments from worker shard X available at a reference chain block proposer L prior to its new proposal P_r. Here, com_i is the latest known block commitment from X that had been included in reference block P_r, P_r is the latest reference block that includes the cross-shard transaction com_2 involving X.

For a block B_j reporting a reference block at height s from X is valid if and only if:

1) Each worker shard block whose hash appear in the hash chain H_j has been signed by at least f + 1 distinct replicas in X; and
2) The block B_j extends the latest committed block B_l of the shard; L validates this using the hash chain H_j mentioned inside the commitment com_j.
3) No cross-shard transaction involving X appears after reference block at height s up until the parent block of P_r.

For example, in Figure 6, P_r at height v is the block L wants to propose and let P_s at height s is the reference block that includes the latest commit com_i of shard X. Also, let P_t at height q be the last reference block that includes a cross-shard transaction involving X. Let com_i and com_j be two newly available commitments from X then commitment com_i is invalid as its violates the third condition mentioned above. Specifically, s reported in com_i is less than t, and P_t includes com_2 a cross-shard transaction involving X. On the other hand, assuming H_j is a valid hash chain, com_j is a valid state commitment since u ≥ t.

For every cross-shard transaction com in L’s transaction pool, it is considered valid if and only if com does not intend to read and write from a key that some preceding transaction already intends to write. Let X_com = {X_1, X_2, · · · , X_m} be the subset of shards that are involved in executing com. Let R_com (a) be the set of keys from shard X_a ∈ X_com that com mentions in its read-set. Also, let com_a be the latest block commitment by shard X_a and W (a) be the set of keys mentioned in the write set of cross-shard transaction that are included after the commit com_a. Then, com is considered valid if and only if,

\[ R_com (a) \cap W (a) = \phi, \ \forall X_a \in X_com \]  (3)

Stated differently, this validation check ensures that every cross-shard transaction reads keys that have not been written to by any other cross-shard transaction since the last commit. This is important as it enables replicas in a worker shard to prove and validate the correctness of data they exchange during execution of cross-shard transactions (see §IV-E).

Figure 7 illustrates how the proposer L validates the cross-shard transactions it observes to include them in its next proposal. Let P_r be the latest reference block with cross-shard transactions com_1, com_2 known to L. Also, let com_1 and com_2 be the latest commitments from shards X_a and X_b respectively. Say L wants to propose the next block P_r. Let us assume that keys key_i (a)’s and key_i (b)’s are maintained by shard X_a and X_b respectively. Let R_com_w and W_com denote the read-write set mentioned in the description of the cross-shard transaction com. Lastly, let’s assume that L has already included com_1, com_3, and com_4 in the P_r it has created so far.

Now, among the remaining transactions from transaction pool of L, i.e., {com_5, com_6, com_7, com_8} in our example, com_7 and com_8 can not be included in P_r as com_7 aims to read from key_i (b) on which com_1 already holds a write-lock. Similarly, com_8 aims to read from keys key_i (b) and key_i (b) that are in write set of com_3 and com_4 respectively. On the contrary, com_5 and com_6 do not have any read-write conflicts with any of the cross-shard transactions included so far.

D. Worker Shard Protocol

Although the protocol for a worker shard is not a consensus protocol, we will borrow the popular leader-based paradigm in consensus protocols. Specifically, one replica serves as the leader. The leader is responsible for proposing new worker blocks, getting them certified by the worker shard, and submitting them to be finalized in the reference chain. The period with a stable leader is called a view. Views are numbered by monotonically increasing integers. If the leader of the current view stops making progress or exhibits any other malicious behaviors – e.g., propose multiple blocks at the same height – replicas of the shard will coordinate to move to the next view, with the next replica in the round robin order as the new leader.

Next, we describe the detailed protocol within a view. This part of the protocol has two phases: a proposal phase and a signing phase.

The proposal phase. Leader L of current view in a worker shard X proposes a new block B_i at height i by broadcasting a propose message to other replicas within the shard. Every proposal contains a view certificate where the first view certificate is obtained after a view change protocol described later in this section. Recall, each new proposal reports a state state after executing all the cross-shard transactions (if any)
known to the leader, followed by some intra-shard transactions. All these transactions are executed atop the last committed state of the shard.

Specifically, when latest known worker block $B_{i-1}$ of shard $X$ is already committed, $L$ extends it by first executing cross-shard transactions that appear since commitment of $B_{i-1}$ atop the committed state and then it executes some intra-shard transactions. Alternatively, when the latest known block $B_{i-1}$ is not yet committed, $L$ extends $B_{i-1}$ if and only if no cross shard transactions appear since the reference block, $P_{r_{i-1}}$, reported in $B_{i-1}$. Otherwise, $L$ proposes a new block atop the latest committed block, say $B_j$, from shard $X$, after executing all the cross-shard transactions known since the last commitment.

Figure 8 illustrates this through an example where $L$ proposes the new block atop $B_{i-1}$ only if $Q_{r_{i-1}, r_i}$ is empty, i.e., no new cross-shard transactions involving $X$ appear after reference block $P_{r_{i-1}}$. Otherwise, $L$ proposes the next worker block atop the latest committed block $B_j$ from worker shard, after executing all transactions in $Q_{r_j, r_i}$. Recall, $Q_{r_j, r_i}$ denotes the set of relevant cross-shard transactions that are included in a reference block since the inclusion of the com$_j$ in the reference block $P_{r_j}$.

The signing phase. Each honest replica $n$ upon receiving the proposal $B_i$, replies with a vote message if the replica is in the same view as the proposal and the proposal is valid. A valid proposal satisfies the following properties.

1) $B_i$ extends $B_j$, the latest committed block known to $n$ and the reference block known to $n$ is at a height greater than or equal to the reference block mentioned in $B_i$.

2) The state mentioned in the proposal satisfies the properties of the honest proposal mentioned earlier.

Once a block $B_i$ is certified (i.e., gathers $f + 1$ signatures), $L$ sends the block commitment com$_i$ for $B_i$ to the reference shard. It is then the responsibility of the replica’s in the reference shard to include com$_i$ in the next available reference block. As mentioned earlier, once the commitment com$_i$ or a commitment of its successor block is included in the reference chain, the worker block $B_i$ is finalized.

Monitoring and replacing the leader. As replicas (including the leader) within each worker shard could be faulty, honest replicas in worker shards continuously monitor the progress of the current leader, and blame the current leader upon detecting faulty behavior. At a high level, an honest replica blames the leader of the current view $v$ by broadcasting a (blame, $v$) message to other replicas within the shard, if no new commitment from their shard appears in the reference chain for a long time. To be precise, suppose an honest replica enters a new view or receives a new reference block containing a commitment from their shard at time $t$. This honest replica expects to see a new commitment from their shard either before $t + T_f$ or in the first reference block after $t + T_f$. We will set $T_f = 7\Delta$ and explain the reasoning behind this timeout value in $\Box$

We call $f + 1$ blame messages against the leader of view $v$ a view-change certificate for view $v$. On receiving a view-change certificate for view $v$, replica $n$ enters the next view $v + 1$ and forwards the view-change certificate to the leader of the view $v + 1$. Upon receiving a view-change certificate for view $v$, the leader of view $v + 1$ sends it to all other replicas and starts proposing new blocks following the aforementioned rules. The cycle continues.

E. Execution of Cross-shard Transaction

Once a cross-shard transaction $q$ appears in the reference chain, the shards involved in its execution, $X_q = \{X_1, \cdots, X_m\}$, exchange the values corresponding to keys mentioned in the read-set of $q$ with each other. Specifically, replicas within every shard $X \in X_q$ request replicas of remaining shard for the committed values of addresses mentioned in the read-set of $q$ that are not maintained by $X$. On receiving responses from shards in $X_q$, each replica validates the received value against the appropriate state commit. Upon correct validation, the proposer of the next worker block executes the cross-shard transactions in the order they appear in the reference block.

To avoid data download on every cross-shard transaction, RIVET batches cross-shard transactions and sends a single download request for all the keys used in all transactions in one reference block. Also, during execution, each shard updates its local state whenever the transaction writes to keys from the local shard.

A few subtleties arise in this process. First, every shard should be aware of the description of every function that gets executed as a part of each cross-shard transaction. For example, if a cross-shard transaction executes functions from two different shards, both shards should be aware of the function description. RIVET addresses this by tagging each smart contract as global or local. Every shard stores descriptions of all global contracts. RIVET uses cross-shard transactions to create global contracts and cross-shard transactions in RIVET can only invoke functions of global contracts. Local smart contracts are created using intra-shard transactions and they only accept intra-shard transactions. Although this may appear to result in considerable overhead, this can be avoided by better programming practices. As illustrated in [20], [21], most of
the contracts in Ethereum are copies of each other. Hence, a better programming practice would be to create standard global libraries for common functionalities such as ERC’20 and Exchanges.

The second subtlety arises from potential mismatch in the read-write set mentioned in the description of a transaction and the read-write set accessed by the transaction during its execution within the worker shards. In such scenarios, each replica aborts execution of the transaction, reverts all the changes caused by its execution so far, and proceeds to the next cross-shard transaction.

V. ANALYSIS

In this section, we will first describe our system model and prove the safety and liveness guarantees of the block certification protocol used inside worker shards of RIVET. We will then analyze the performance of RIVET and compare it against the 2PC based approach.

A. System Model

RIVET considers the partially synchronous network model, i.e., a network that oscillates between periods of synchrony and periods of asynchrony. During periods of synchrony all messages sent by honest replicas adhere to to a known delay bound $\Delta$. During periods of asynchron y messages, messages can be delayed arbitrarily. In theory, the partial synchrony model [22] is often stated differently for rigor or convenience, but the essence is to capture the practical timing model mentioned above.

We assume that at most $f$ replicas can be faulty in each shard. Recall that very shard in 2PC has $3f + 1$ replicas whereas in RIVET, only the reference shard has $3f+1$ replicas and every worker shard has $2f + 1$ replicas. All faulty replicas are controlled by a single adversary $A$ and can deviate arbitrarily from the prescribed protocol. All non-faulty replicas are honest and they strictly follow the prescribed protocol. We assume that $A$ can not break standard cryptographic constructions of hash functions and signatures schemes.

B. Safety and Liveness

Safety of RIVET follows directly from the safety of the Byzantine fault tolerant consensus protocol used in the reference shard. This holds true even during periods of asynchrony because the partially synchronous consensus algorithm provides safety even under asynchrony. To elaborate, the consensus algorithm in the reference shard provides global order for all transactions, the intra-shard ones as well as cross-shard ones. Each transaction is associated with a unique reference block that finalizes it in the reference chain. Transactions are hence ordered first by their heights in the reference chain, and then by their positions inside the reference block.

Besides an agreed upon total order, RIVET also ensures every worker block commitment finalized in the reference chain represents a valid statement. The reference shard ensures that at most one worker block at any given height from a shard gets finalized and it extends a previously finalized worker block in that shard.

We next show that RIVET makes progress during periods of synchrony, i.e., when messages between pair of honest replicas gets delivered within a bounded delay of $\Delta$. Specifically, during periods of synchrony, there exists a bounded time $T_f = 7\Delta$ such that if all worker replicas are in the same view, the leader of the view is honest, and the reference chain makes progress then each worker will make progress as well. To see this, consider the shard $X$ and let $P_r$ be the latest reference block. Let $t$ be the time instant when $P_r$ is created. This implies that by time $t + \Delta$, every honest replica of shard $X$ including the proposer of the next block, $L$, will be aware of the block $P_r$. Also, since each replica of every shard is connected with at least one honest replica of every other shard, by time $t + 3\Delta$ every honest replica of shard $X$ will have the required state to execute the cross-shard transactions in blocks up to $P_r$.

Hence, when $L$ proposes the next block at time $t+3\Delta$, every honest replica will respond immediately with its signature. Thus, by time $t + 5\Delta$, $L$ will collect a certificate for its proposal, and by time $t+6\Delta$, the block commitment will reach an honest replica of reference chain. Also, by time $t + 7\Delta$ it will reach the leader of the reference chain. This implies that the commitment of worker block or one of its successors will appear in the next reference block.

C. Performance Analysis

It is easy to see that in both RIVET and 2PC based approach, each worker shard only stores a subset of the entire state. Hence, both approaches achieve state sharding. Also, each worker shard validates a subset of all intra-shard transactions and the cross-shard transactions it is a part of. Hence, both protocols achieve computation sharding. Moreover, since the reference shard runs a standard BFT consensus protocol, the communication complexity of finalizing a reference block is same as the communication complexity of the underlying consensus protocol, e.g., HotSuff only requires linear communication.

Contrary to reference blocks, finalization of a worker block $B_i$ in RIVET involves two steps: certification of $B_i$ and finalization of the reference block that includes the commitment $com_i$ of $B_i$. It is easy to see from (IV-D) that certification of every worker block involves only one round of communication: the leader broadcasts a new proposal to each replica and they respond with their signatures. Since both these steps have linear communication costs, overall block certification protocol has linear costs as well. Hence, assuming a linear consensus protocol in the reference chain, the overall communication of finalizing a worker block is also linear. An important point to note is that each reference block will potentially include numerous block commitments and cross-shard transactions simultaneously, and hence the communication overhead gets amortized.

Confirmation latency of transactions. The cross-shard transaction $ctx$ is finalized as soon as $ctx$ gets included in a
reference block. The state atom which ctx should be executed has also been finalized by then. The only thing remaining is to get the actual execution result, i.e., the resulting state modification due to executing ctx. Since every shard involved executes ctx deterministically atop an identical state, this execution result becomes available as soon as one worker shard block containing ctx gets certified. It does not matter which participating worker worker shard first does so. Hence, the confirmation latency of a cross-shard transaction is measured as the time elapsed since its inclusion in the reference chain till the first worker block containing it gets certified.

We measure the confirmation latency of an intra-shard transaction as the elapsed time between its inclusion in a worker block and the finalization of worker shard block. Note that in 2PC, worker blocks are finalized immediately and so are the intra-shard transactions in them.

VI. IMPLEMENTATION & EVALUATION

We implement IVET and 2PC atop the open-source Quorum client version 2.4.0 [12]. Quorum is a fork of the Ethereum Go client and inherits Ethereum’s smart contract execution platform and implements a permissioned consensus protocol based on the Istanbul BFT (IBFT) and Tendermint [23] consensus algorithm.

For IVET, we use the IBFT implementation for the reference shard, and we implement the protocol described in [IV-D] for each worker shard.

For 2PC, we use the IBFT implementation for all shards. Since existing 2PC based approaches primarily focuses on the UTXO model or other specialized computation models (ref. [VII]), we need to implement additional support to extend 2PC to Ethereum’s generic smart contract model. We next describe implementation details for 2PC with generic computation in [VI-A]

A. 2PC Implementation Details

A coordinator shard manages all cross-shard transactions [7]. We refer to the blockchain maintained by the coordinator shard as the coordinator chain. Users send cross-shard transactions along with their potential read-write set to the coordinator shard. The leader of the coordinator shard validates these transactions for read-write conflicts and, on successful validation, proposes them to be included in the coordinator chain. Every cross-shard transaction upon its inclusion in the coordinator chain acquires an explicit lock on the set of keys in its read-write set. Similar to IVET, the coordinator shard includes a new cross-shard transaction only if the transaction does not conflict with any of the pending cross-shard transactions.

Worker shards monitor the coordinator chain for new cross-shard transactions. Upon noticing a new cross-shard transaction ctx, involved worker shards commit to a state of the keys mentioned in the read-set of ctx. Each commitment also carries a proof generated by running consensus within the worker shard. Once the worker proposal is finalized, every replica locks the keys mentioned in the read-write set of ctx from any other conflicting transaction until it executes ctx. Once commitments from all involved shards appear in the coordinator chain, these shards follow the same procedure as IVET for data fetching and transaction execution. Upon execution, worker shard replicas unlock the keys in ctx and send an acknowledgment message to the coordinator shard – at this point, the keys become accessible to future intra-shard transactions.

B. Experimental Setup.

Our experimental setup consists of six worker shards and one reference shard. Each shard tolerates \( f = 3 \) Byzantine faults. Thus, each worker shard in IVET consists of 7 nodes \((2f + 1)\) and the reference shard consists of 10 nodes \((3f + 1)\). We vary each shard in 2PC consists of 10 nodes \((3f + 1)\). We run all nodes on Amazon Web Services (AWS) t3a.medium virtual machines (VM) with one node per VM. All VMs have 2 vCPUs, 4GB RAM, and 5.0 GB/s network bandwidth. The operating system is Ubuntu 18.04 and the Golang compiler version is 1.13.6.

Node and network topology. We create an overlay network among nodes with the following connectivity. Nodes within a shard are pair-wise connected, i.e., form a complete graph. In addition, each node is connected to \( f + 1 \) randomly chosen nodes from every other shard.

We mimic a setting where each node is placed in one of 10 geographical locations across different continents. Instead of placing nodes physically there, we use the measured ping latency [26] for every pair of locations and then use the Linux tc tool to insert the corresponding delay to every message. We maintain the same network topology and network latency for all our experiments.

Evaluation methodology. We run both IVET and 2PC for approximately 50 reference and coordinator blocks after an initial stabilization period. Every worker shard in both IVET and 2PC generate blocks after every \( I_{w} = 5 \) seconds. We vary the block interval of the reference chain and coordinator chain to be \( I_{r} = 10, 15, \) and 20 seconds. From hereon, we refer to the ratio \( I_{r}/I_{w} \) as the reference-worker block interval ratio, which takes the values of 2, 3, and 4 in our experiments. We test both designs using the benchmark we created in [III] from historical Ethereum transactions from 4000 blocks starting at block height 7.39 Million. This trace comprises of approximately 14000 cross-shard transactions. To facilitate such evaluation, we initialize each shard with the code and state of relevant smart contracts. In all our experiments, we broadcast a new batch of cross-shard transactions of fixed size after every reference or coordinator block. We refer to this batch size as the cross-shard injection rate, and test both designs with cross-shard input rate of 100, 200 and 400.

\(^{3}\)Saltini and Hyland-Wood in [24] discusses a liveness bug in the original design of IBFT. The bug has been fixed since then in [25].
C. Experiments and Results

Confirmation latency. We first evaluate the confirmation latency of transactions. Figure 9 gives the average confirmation latency of cross-shard transactions in RIVET and 2PC under varying cross-shard input rate and reference-worker block interval ratios. The confirmation latency of a cross-shard transaction is the time elapsed since its inclusion in a reference block till its inclusion in any one of the participating shard’s worker blocks (ref. VI-C). Observe that the cross-shard confirmation latency of RIVET only depends on the worker shard block generation interval. On the contrary, cross-shard transaction execution in 2PC requires at least one additional reference block. Hence, the average confirmation latency of cross-shard transactions in 2PC is approximately \( \frac{1}{w} \). As a result, we see an increase in the confirmation latency for 2PC as \( \frac{1}{w} \) increases.

Recall from VI-C we measure the confirmation latency of an intra-shard transaction \( t_x \) as the elapsed time between its inclusion in a worker shard block and the time when the worker shard block is finalized. In 2PC, since every worker shard runs a consensus protocol, the worker blocks and the intra-shard transactions in them are finalized instantly. In RIVET, however, worker shard blocks and the intra-shard transactions in them are confirmed only when their commitments (or commitments of their successor blocks) are finalized in the reference chain. In all our experiments with RIVET, we observe that (not shown) commitments of almost all (> 99%) blocks get included in the next reference block. Thus, the confirmation latency of intra-shard transaction in RIVET is less than one reference block interval.

Throughput of cross-shard transactions. For a given cross-shard injection rate, we measure the cross-shard output rate in both RIVET and 2PC as the average number of cross-shard transactions included in every reference block and coordinator block, respectively.

Figure 10 illustrates the cross-shard output rate of RIVET and 2PC under varying cross-shard injection rate and reference-worker block interval ratios. Recall from VI-A that the reference and the coordinator chains only include non-conflicting transactions in them, and hence we do not observe the cross-shard output rate to be the same as the cross-shard injection rate in any of the experiments. However, in all our experiments of RIVET, we observe that the cross-shard output rate is greater than 70% of the cross-shard injection rate whereas cross-shard output rate of 2PC is approximately 45% of the corresponding cross-shard injection rate. The reason is that 2PC holds locks on its keys for at least one intermediate coordinator block which results in higher conflicts during the inclusion of newer cross-shard transactions. On the other hand, conflicts in RIVET can be resolved prior to the next reference block. Lastly, as anticipated, the absolute value of cross-shard output rate increases linearly with increase in cross-shard injection rate, as the proposer of the reference chain in RIVET (coordinator chain in 2PC) has a larger number of transactions to choose from for each new reference block.

Fraction of committed worker blocks. Figure 11 illustrates the average fraction of certified worker shard blocks that successfully get committed to the reference chain under varying cross-shard batch sizes and reference-worker block interval ratios. In all experiments, approximately 90% of the worker shard blocks get finalized. This fraction remains consistent across different cross-shard batch sizes and reference-worker block interval ratios.

Upon closer inspection, we observe that almost all of the 10% of discarded certified blocks are certified very close to some reference blocks. The commitments of these certified blocks did not make it to reference chain because the nearby reference block contains cross-shard transactions involving the respective shards. An interesting technique to reduce discarded worker blocks is thus to have a better timing coordination between reference and worker shards, which we leave as future work.

Other findings. In addition to the above results, we observe that more than 99% of the state commitments in RIVET are included in the immediate successor reference block. Almost all commit messages in 2PC are also included in the immediate
successor coordinator block. Each node successfully downloads the data required for a cross-shard transactions within the first two seconds of hearing about the cross-shard transaction. These observations are consistent across all our experiments.

VII. RELATED WORK

RIVET is partially inspired by the approach of Deterministic Transactions Execution (DTE) in distributed databases [17]. In DTE all servers (shards in our case) first agree on an ordered list of transactions and then deterministically execute them in the agreed order. Abadi et al. [27] give a great overview of the recent progress and improvements of DTE. DTE are be made to avoid single points of failure by replicating each server across multiple replicas using a crash fault-tolerant consensus protocol such as Paxos [28]. At some level, RIVET can be viewed as a method to make DTE Byzantine fault tolerant. But RIVET also differs from fault-tolerant DTE in two major ways: First, RIVET tolerates Byzantine failure without using any consensus algorithm within the worker shards. Second, DTE globally orders all the transactions before executing them; in contrast, cross-shard transactions are ordered before being executed whereas intra-shard transactions are optimistically executed before being ordered.

Blockchain sharding. Previous blockchain sharding proposals primarily focus on increasing the overall throughput of the entire system, with minimal emphasize on characterizing and handling cross-shard transactions [4], [6]–[8], [29], [30]. As summarized in [31] almost all prior works use minor variants of 2PC for cross-shard transactions.

RS-Coin [29] and Omniledger [5] are client driven sharded systems in the UTXO model where cross-shard transactions are executed using 2PC. RS-Coin is a permissioned system whereas Omniledger considers a permissionless model. Chainspace [4] also uses a variant of 2PC for cross-shard transaction where it substitutes the client by a inter-shard consensus protocol called S-BAC. RapidChain [6] also considers UTXO based model where cross-shard transactions are replaced by dummy transactions at every participating shard. These dummy transactions maintain semantic properties of the original cross-shard transactions. To execute a cross-shard transaction, shards involved in the transaction run 2PC protocol with every output shard, playing the role of the 2PC transaction coordinator and input shards being the server.

Monoxide [8] partitions its participants into shards where nodes in each zone run PoW. Monoxide also adopts UTXO based data model and runs 2PC for cross-shard transaction. Cross shard transactions are executed in the initiator shards and then the proofs are sent to the receiver shards. Note that since Monoxide uses PoW, the receiver shard needs to wait for a long duration before it can confidently use the certificates from initiator shard. Cross shard transactions in [7] use two-phase locking (2PL) and two phase commit (2PC) to achieve atomicity and isolation in cross-shard transactions. To defend against attacks from clients who can lock-up shared resources for long periods, they replace clients by a distributed committee. They demonstrate that Rapid-up shared resources for long periods, they replace clients by a distributed committee. They demonstrate that RapidChain does not achieve atomicity in non-UTXO model.

State Partitioning. Our partitioning technique shares similarities with Schism [32], a database partitioning system for distributed databases. Schism models the database as a graph, where a vertex denotes a single record/tuple and an edge connects two records if they are accessed by the same transaction. A recent work Optchain [33] improves the placement of transaction in a sharded blockchain to reduce the fraction of cross-shard transaction. In contrast to our graph representation, Optchain models transactions as nodes and transaction dependencies as edges. It deals only with the UTXO model. It also places more emphasis on temporal balancing, where the number of nodes in each shard must be the same at all times. A concurrent work [34] focuses on increasing throughput by creating individual shards for transactions that solely access one particular contract and a single shard for transactions that access multiple contracts. These works do not address the problem of efficient execution of cross-shard transactions.

Sharding and off-chain based solutions. Off-chain solutions [35]–[40] represent an alternative direction to improve blockchain scalability. We observe that off-chain solutions and sharding solutions have deep connections. This is not obvious at all from the current state of the literature partly because the two approaches start out with very different motivations. Off-chain solutions shard part of their state/UTXOs among many subset of $n$ nodes ($n = 2$ for payment channels). These nodes process local transactions, maintain the latest information about the assigned state and use the consensus engine, i.e., the blockchain, to order them globally relative to other shards. Furthermore, these shards (group of $n$ nodes) typically use a timing-based dispute resolution mechanism to tolerate node failures. Recent off-chain based protocols such as [38]–[40] extend the dispute resolution using incentives. At their core, sharding schemes have a similar structure. Typically they use full-fledged consensus within every shard and some coordination schemes (so far 2PC) between shards to get rid of the global consensus engine. Our paper deviates from
this conventional wisdom by removing consensus from the worker; it is thus like a hybrid of both sharding and off-chain scalability solutions.

VIII. CONCLUSION AND FUTURE DIRECTIONS

We have presented RIVET, a new paradigm for executing cross-shard transactions in a sharded system. RIVET has low latency and high throughput for cross-shard transactions in comparison with the 2PC approach. Also, only the reference shard in RIVET is required to run a consensus protocol; worker shards only vouch for the validity of blocks, and hence they require fewer replicas and less communication. It is plausible to substitute the reference chain with a hierarchy of reference chains each coordinating commitments and cross-shard transactions between a subset of worker shards. Such a hierarchical design would allow the system to process more cross-shard transactions concurrently. Furthermore, such a design may better exploit locality of interaction between different subsets of shards. Extending our implementation and evaluation framework to a hierarchical design is a promising future research direction.

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