

Divide and Scale: Formalization of Distributed Ledger Sharding Protocols

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Abstract—Sharding distributed ledgers is the most promising on-chain solution for scaling blockchain technology. In this work, we define and analyze the properties a sharded distributed ledger should fulfill. More specifically, we show that a sharded blockchain cannot be scalable under a fully adaptive adversary, but it can scale up to $O(n/\log n)$ under an epoch-adaptive adversary. This is possible only if the distributed ledger employs a checkpoint process at the end of each epoch. Our model builds upon and extends the Bitcoin backbone protocol by defining *consistency* and *scalability*. Consistency encompasses the need for atomic execution of cross-shard transactions to preserve safety, whereas scalability encapsulates the speedup a sharded system can gain in comparison to a non-sharded system. Lastly, we analyze existing sharded blockchains and either show their correctness (OmniLedger, RapidChain) under our model or pinpoint where they fail to balance the consistency and scalability requirements (Elastico, Monoxide).

I. INTRODUCTION

One of the most promising solutions to scaling blockchain protocols is sharding [18], [20], [32], [33]. The high-level idea of sharding is to employ multiple blockchains in parallel, the *shards*, that operate under the same consensus rules. Participants of the consensus only validate transactions for one shard, so that the system can “scale-out”. Unfortunately, there is no formal definition for a robust sharded ledger (similar to the definition of what a robust transaction ledger is [10]).

The lack of formalization allows every protocol to define its own set of goals, which tend to favor the presented system design. These goals are then confirmed achievable by experimental evaluations that demonstrate their improvements. However, the experiments are typically conducted under different models and cannot incorporate Byzantine behavior from the adversary. Thus, the evaluation and comparison – if possible at all – is at best optimistic.

In this work, we take up the challenge of providing “common grounds” under which we can capture the sharding limitations and fairly evaluate different sharding solutions. We achieve this by defining a formal sharding framework. Then we apply our framework to four different sharded ledgers and either prove their properties or identify why they do not model our definition of a robust sharded transaction ledger. To achieve this we need to address three key challenges. First, we need to maintain compatibility with the existing models of a robust sharded transaction ledger, so that the sharding framework constitutes a strict generalization. Second, our model needs to maintain enough relation with multiple existing sharded ledgers in order to be of practical use. Finally,

in order to provide a fair comparison and directions for future research we need to provide formal bounds of what a sharded transaction ledger can achieve.

To address the first two challenges, we build upon the work of Garay et al. [10]. We modify the blockchain transaction ledger properties, originally introduced in [10], namely *Persistence* and *Liveness*, to fit our framework. Persistence essentially expresses the agreement between honest parties on the transaction order, while liveness encompasses that a transaction will eventually be processed and included in the transaction ledger. Further, we extend the model to capture what sharding offers to blockchain systems by defining *Consistency* and *Scalability*. Consistency is a security property that conveys the atomic property of cross-shard transactions (either aborted or committed in all shards). Scalability, on the other hand, is a performance property that encapsulates the speedup of a sharded blockchain system compared to a non-sharded blockchain system.

Next, we address the third challenge by exploring the boundaries of sharding protocols in order to maintain the security and performance properties of our framework. We observe a fine balance between consistency and scalability. **To truly work, a sharding protocol needs to scale in three dimensions: bandwidth, storage, and computation.**

First, the computational cost of each participant in a blockchain system is dominated by the consensus verification process. In sharding protocols, each participant must only participate in the verification process of a constant number of shards to satisfy scalability. Second, the bandwidth bottleneck traditionally appears due to the high communication complexity of the underlying protocols, i.e., consensus of shards and handling transactions across different shards (cross-shard transactions). In this work, we show that there is no sharding protocol that can scale better than the blockchain substrate if participants maintain information on all shards corresponding to the cross-shard transactions of their own shard. Finally, we identify a clear trade-off between the storage necessity and how adaptive the adversary is. If the adversary is somewhat adaptive, maintaining security requires shard reassignments and the participants need to store the blockchain of the new shard in order to verify new transactions. In this work, we prove that there is no sharding protocol that scales better than the blockchain substrate against an adaptive adversary. Furthermore, we show that all sharding protocols must employ a checkpoint process; otherwise, the storage requirements of

each participant will eventually be proportional to the storage requirements of a non-sharded protocol.

Once we address our challenges and provide solid limits and bounds on the design of a sharding protocol, we evaluate popular sharding protocols under our model. Specifically, we describe, abstract and analyze Elastico [20], Monoxide [32], OmniLedger [18] and RapidChain [33]. We demonstrate that both Elastico and Monoxide fail to meet the desired properties – particularly scalability and/or consistency– and thus do not actually improve on non-sharded blockchains according to our model. On the contrary, we prove that OmniLedger (in our model) and RapidChain (in a weaker network and threat model) satisfy the desired sharding properties. For both protocols, we provide elaborate proofs and estimate also how much they improve on their blockchain substrate. To that end, we define and use a throughput factor, that expresses the average number of transactions that can be processed per round. We show that both OmniLedger and RapidChain scale optimally, reaching the upper bound $O(\frac{n}{\log n})$.

In summary, the contribution of this work is the following:

- We introduce a framework where sharded transaction ledgers are formalized and the necessary properties of sharding protocols are defined. Further, we define a throughput factor to estimate the transaction throughput improvement of sharding blockchains over non-sharded blockchains (Section II).
- We provide the limitations of secure and efficient sharding protocols under our model (Section III).
- We evaluate existing protocols under our model. We show that Elastico and Monoxide fail to satisfy some of the defined properties, whereas OmniLedger and RapidChain satisfy all the necessary properties to maintain a robust sharded transaction ledger (Section IV).
- We present the necessary ingredients for designing a robust sharded ledger (Section V).

Omitted proofs can be found in the Appendix.

II. THE SHARDING FRAMEWORK

In this section, we introduce a formal definition of sharded transaction ledgers and define the desired properties of a secure and efficient distributed sharded ledger. Further, we employ the properties of blockchain protocols defined by Garay et al. [10], which we assume to hold in every shard. Given these properties, we later evaluate if the existing sharding protocols maintain secure and efficient sharded transaction ledgers. In addition, we define a metric to evaluate the efficiency of sharding protocols, the transaction throughput.

A. The Model

Time and Adversary. We analyze blockchain protocols assuming a synchronous communication network. In particular, a protocol proceeds in *rounds*, and at the end of each round the participants of the protocol are able to synchronize, and all messages are delivered. A set of R consecutive rounds $E = \{r_1, r_2, \dots, r_R\}$ defines an *epoch*. We consider a fixed number of participants in the system denoted by n . However,

this number might not be known to the parties. The adversary is slowly-adaptive, meaning that the adversary can corrupt parties on the fly at the beginning of each epoch but cannot change the malicious set of participants during the epoch, i.e., the adversary is static during each epoch. In addition, in any round, the adversary decides its strategy after it gets to see all honest parties' messages. The adversary can change the order of the honest parties' messages but cannot modify or drop them. Furthermore, the adversary is computationally bounded and can corrupt at most f parties during each epoch. This bound f holds strictly at every round of the protocol execution. Note that depending on the specifications of each protocol, i.e., which Sybil-attack-resistant mechanism is employed, value f represents a different manifestation of the adversary's power (e.g., computational power, stake in the system).

Transaction model. In this work, we assume transactions consist of inputs and outputs that can only be spent as a whole. Each transaction input is an unspent transaction output (UTXO). Thus, a transaction takes UTXOs as inputs, destroys them and creates new UTXOs, the outputs. A transaction ledger that handles such transactions is UTXO-based (as opposed to a typical account-based database), similarly to Bitcoin [23]. Note that transactions can have multiple inputs and outputs. We define the average size of a transaction, i.e., the average number of inputs and outputs of a transaction in a transaction set, as a parameter v . Further, we assume a transaction set T follows a distribution D_T (e.g. D_T is the uniform distribution if the sender and receiver of each transaction are chosen uniformly at random). All sharding protocols considered in this work are UTXO-based.

B. Sharded Transaction Ledgers

A sharded transaction ledger is defined as a collection of sets $S = \{S_1, S_2, \dots, S_m\}$, where each set $S_i, i \in [m] = \{1, 2, \dots, m\}$ represents valid ledgers of a shard, and a set of transactions T , each one possessing an efficient membership test. A ledger of a shard $x \in S_i$, for $i \in [m]$, is a vector of sequences of transactions $x = \langle x_1, x_2, \dots, x_l \rangle$, where $tx \in x_j \Rightarrow tx \in T, \forall j \in [l]$.

In a sharding blockchain protocol, a sequence of transactions $x = tx_1 \dots tx_e$ is inserted in a block which is appended to a party's local chain C in a shard. A chain C of length l contains the ledger $x_C = \langle x_1, x_2, \dots, x_l \rangle$ if the input of the j -th block in C is x_j . The *position* of transaction tx_j in the ledger of a shard x_C is the pair (i, j) where $x_i = tx_1 \dots tx_e$ (i.e., the block that contains the transaction). Essentially, a party *reports* a transaction tx_j in position i only if its local ledger of a shard includes transaction tx_j in the i -th block. We assume that a block has constant size, meaning there is a maximum constant number of transactions included in each block. Furthermore, we define a symmetric relation on T , denoted by $M(\cdot, \cdot)$, that indicates if two transactions are conflicting, i.e., $M(tx, tx') = 1 \Leftrightarrow tx, tx'$ are conflicting.

Next, we introduce the essential properties a blockchain protocol must uphold to maintain a robust and efficient sharded

transaction ledger: *persistence*, *consistency*, *liveness*, *scalability*. *Persistence* and *consistency* are security properties, while *liveness* and *scalability* are performance properties.

Intuitively, *persistence* expresses the agreement between honest parties on the transaction order, whereas *consistency* conveys that cross-shard transactions are either committed or aborted in all shards. On the other hand, *liveness* indicates that transactions will eventually be included in a shard, i.e., the system makes progress. Last, *scalability* encapsulates the speedup a sharded system can gain in comparison to a non-sharded blockchain system: The blockchain throughput limitation stems from the need for data propagation, maintenance, and verification from every party. Thus, to scale a blockchain protocol via sharding, each party must broadcast, maintain and verify mainly local information.

Definition 1 (Persistence). *Parameterized by $k \in \mathbb{N}$ (depth parameter), if in a certain round an honest party reports a shard that contains a transaction tx in a block at least k blocks away from the end of the shard (such transaction will be called stable), then whenever tx is reported by any honest party it will be in the same position in the shard.*

Definition 2 (Consistency). *Parametrized by $k, v \in \mathbb{N}$ and D_T (depth parameter, average size of transactions and distribution of the input set of transactions, resp.), there is no round r in which there are two honest parties P_1, P_2 reporting transactions tx_1, tx_2 respectively as stable (at least in depth k in the respective shards), such that $M(tx_1, tx_2) = 1$.*

To evaluate the progress of the system, we assume that the block size is sufficiently large, and thus a transaction will never be excluded due to space limitations.

Definition 3 (Liveness). *Parameterized by $u, k, v \in \mathbb{N}$ and D_T (wait time, depth parameter, average size of transactions and distribution of the input set of transactions resp.), provided that a valid transaction is given as input to all honest parties of a shard continuously for the creation of u consecutive blocks, then all honest parties will report this transaction at least k blocks from the end of the shard, i.e., all report it as stable.*

Scaling distributed ledgers depends on three vectors: bandwidth, storage, and computational power. In particular, to allow high transaction throughput all these factors must scale as a function of the number of participants in the system. First, we define a communication scaling factor ω_m as the communication complexity of the protocol scaled over the number of participants. In essence, ω_m represents the average number of messages per participant in a protocol execution.

If we assume an efficient diffusion mechanism of data (gossip protocols) in the system, and considering only information relevant to the system's progress, communication complexity collapses to space complexity. Essentially, every party in the system only propagates and receives the information that is useful to it and this information (e.g., blocks, unspent transaction outputs, transactions, etc.) is eventually stored in the party's collection of ledgers. We introduce a space scaling

factor ω_s that estimates the space complexity of a sharding protocol, i.e., how much data is stored in total by all the participants of the system in comparison to a single database that only stores the data once. The space scaling factor takes values from $O(1)$ to $O(n)$, where n is the fixed number of participants in the protocol. For instance, the Bitcoin protocol has scaling factor $O(n)$ since every party needs to store all data, while a perfectly scalable blockchain system has a constant space scaling factor.

To define the space scaling factor we need to introduce the notion of average-case analysis. Typically, sharding protocols scale well for a best-case analysis, in essence for an input T that does not contain cross-shard nor multi-input (multi-output) transactions. However, in practice transactions are both cross-shard and multi-input/output. For this reason, we define the space scaling factor as a random variable dependent on an input set of transactions T drawn uniformly at random from a distribution D_T .

We assume T is given well in advance as input to all parties. To be specific, we assume every transaction $tx \in T$ is given at least for u consecutive rounds to all parties of the system. Hence, from the liveness property, all transaction ledgers held by honest parties will report all transactions in T as stable. Further, we denote by $x^{[k]}$ the vector x where the last k positions are “pruned”, while $|x^{[k]}|$ denotes the number of transactions contained in this “pruned” ledger. We note that a similar notation holds for a chain C where the last k positions map to the last k blocks. Each party P_i maintains a collection of ledgers $L_i = \{x_1, x_2, \dots, x_s\}, 1 \leq s \leq m$. We define the scaling factor for a sharding protocol with input T as the number of stable transactions included in every party's collection of transaction ledgers over the number of transactions given as input in the system¹,

$$\omega_s(T) = \sum_{\forall i \in [n]} \sum_{\forall x \in L_i} |x^{[k]}| / |T|$$

Note that for a typical blockchain protocol with a single chain, the expected space scaling factor is $\omega_s = n$ since every party maintains a copy of all the transactions of the input T .

Apart from space and communication complexity, we also consider the verification process, which can be computationally expensive. In our model, we assume the computational cost is constant per verification. Every time a party checks if a transaction is conflicting with a ledger, the running time is considered constant since this process can always speed up using efficient data structures (e.g. trees allow for logarithmic lookup time). Therefore, the computational power spent by a party for verification is defined by the number of times the party executes the verification process. For this purpose, we employ a (verification) oracle, denoted by $V(T, S)$ which takes as input a transaction $tx \in T$ and a valid ledger $x \in S$ and checks whether they are conflicting; formally, $V(tx, x) = 1 \Leftrightarrow \exists tx' \in x$ s.t. $M(tx, tx') = 1$. Each party

¹Without loss of generality, we assume all transactions are valid and thus are eventually included in all honest parties' ledgers.

calls the oracle to verify transactions, pending or included in a block. We denote by q_i the number of times party P_i calls oracle V during the protocol execution. We now define a computational scaling factor ω_c that reflects the total number of times all parties call the verification oracle during the protocol execution scaled over the number of input transactions,

$$\omega_c(T) = \sum_{\forall i \in [n]} q_i / |T|$$

Note that similarly to the space scaling factor, the computational scaling factor is also a random variable. Hence, the objective is to calculate the expected value of ω_c , i.e., the probability-weighted average of all possible values, where the probability is taken over the input transactions T .

In an ideally designed protocol, communication, space, and computational scaling factors express the same amount of information. However, there can be poorly designed protocols that scale in only one dimension but fail in scaling the entire system. For this reason, we consider the overall scaling factor to be the maximum of the three factors,

$$\omega = \max(\omega_m, \omega_s, \omega_c)$$

. Intuitively the scaling factor is the denominator of the overall scalability of a system (i.e. if scaling factor is $O(\log n)$ then the scalability is $O(n/\log n)$).

Definition 4 (Scalability). *Parameterized by $n, v \in \mathbb{N}, D_T$ (number of participants, average size of transactions and distribution of the input set of transactions, resp.), a sharding blockchain protocol has expected scaling factor $\omega = o(n)$.*

We say that the protocol Π satisfies property Q in our model if Q holds with high probability (in a security parameter). Note that an event happens with high probability if it happens with probability $p_n \geq 1/n^c$ for a security parameter $c > 0$.

We say that a sharding protocol that satisfies the properties of persistence, consistency, liveness, and scalability maintains a *robust sharded transaction ledger*.

C. (Sharding) Blockchain Protocols

In this section, we adopt the definitions and properties of Garay et al. [10] for blockchain protocols, while we slightly change the notation to fit our model. In particular, we assume the parties of a shard of any sharding protocol maintain a chain (ledger) to achieve consensus. This means that every shard internally executes a blockchain (consensus) protocol that has three properties as defined by [10]: chain growth, chain quality, and common prefix. Each consensus protocol satisfies these properties with different parameters.

In this work, we will use the properties of the shards' consensus protocol to prove that a sharding protocol maintains a robust sharded transaction ledger. In addition, we will specifically use the shard growth and shard quality parameters to estimate the transaction throughput of a sharding protocol. The following definitions follow closely Definitions 3, 4 and 5 of [10].

Definition 5 (Shard Growth Property). *Parametrized by $\tau \in \mathbb{R}$ and $s \in \mathbb{N}$, for any honest party P with chain C , it holds that for any s rounds there are at least $\tau \cdot s$ blocks added to chain C of P .*

Definition 6 (Shard Quality Property). *Parametrized by $\mu \in \mathbb{R}$ and $l \in \mathbb{N}$, for any honest party P with chain C , it holds that for any l consecutive blocks of C the ratio of honest blocks in C is at least μ .*

Definition 7 (Common Prefix Property). *Parametrized by $k \in \mathbb{N}$, for any pair of honest parties P_1, P_2 adopting chains C_1, C_2 (in the same shard) at rounds $r_1 \leq r_2$ respectively, it holds that $C_1^{[k]} \preceq C_2$, where \preceq denotes the prefix relation.*

We can now define an efficiency metric, the transaction throughput of a sharding protocol. Considering constant block size, we define the transaction throughput as follows:

Definition 8 (Throughput). *The expected transaction throughput in s rounds of a sharding protocol with m shards is $\mu \cdot \tau \cdot s \cdot m'$, where m' denotes the degree of parallelism in the system. We define the throughput factor of a sharding protocol $\sigma = \mu \cdot \tau \cdot m'$.*

Intuitively, the throughput factor expresses the average number of blocks that can be processed per round by a sharding protocol. Thus, the transaction throughput (per round) can be determined by the block size multiplied by the throughput factor. The block size is considered constant, however, it cannot be arbitrarily large. The limit on the block size is determined by the bandwidth of the “slowest” party within each shard. Note that our goal is to estimate the efficiency of the parallelism of transactions in the protocol, and thus other factors like the cross-shard communication latency are omitted.

The degree of parallelism of a sharding protocol m' highly depends on the number of shards m as well as the average size of transactions v . To evaluate the degree of parallelism of a protocol, we need to determine how many shards are affected by each transaction on average; essentially, estimate how many times we run consensus for each valid transaction until it is stable. This is determined by the mechanism that handles the cross-shard transactions.

III. LIMITATIONS OF SHARDING PROTOCOLS

In this section, we explore the limits of sharding protocols. First, in Section III-A, we focus on the limitations that stem from the nature of the transaction workload. In particular, sharding protocols are affected by two characteristics of the input transaction set: the number of inputs and outputs of each transaction v , and more importantly the number of cross-shard transactions.

The number of inputs and outputs (UTXOs) of each transaction is in practice fairly small. For example, an average Bitcoin transaction has 2 inputs and 3 outputs with a small deviation (e.g., 1) [1]. Hence, in this work we consider the number of UTXOs participating in each transaction fixed, thus

v is a small constant. Note that in a worst-case analysis for estimating the ratio of cross-shard transactions $v = 2$.

The number of cross-shard transactions depends on the distribution of the input transactions D_T , as well as the process that partitions transactions to shards. First, we assume each ledger interacts (i.e., has a cross-shard transaction) with s other ledgers on average, where s is a function dependent on the number of shards m . We consider protocols that require parties to maintain information on shards other than their own and derive an upper bound for the expected value of s such that scalability holds. Then, we prove there is no protocol that maintains a robust sharded ledger against an adaptive adversary.

Later, in Section III-B, we assume shards are created with a uniformly random process; essentially the UTXO space is partitioned uniformly at random into shards. Under this assumption (which most sharding systems make), we show all transactions are expected to be cross-shard, and there is no sharded ledger that satisfies scalability if participants have to maintain any information on ledgers others than their own.

Last, in Section III-C, we examine the case where parties are assigned to shards independently and uniformly at random. We show that any sharding protocol can scale at most by a factor of $n/\log n$. Finally, we demonstrate the importance of checkpoints in sharding protocols; we prove there is no sharding protocol that maintains scalability in our security model without a checkpoint process².

A. General Bounds

First, we prove there is no robust transaction ledger that has a constant number of shards. Then, we show that there is no protocol that maintains a robust sharded transaction ledger against an adaptive adversary.

Theorem 9. *In any robust sharded transaction ledger the number of shards (parametrized by n) is $m = \omega(1)$.*

Suppose a party is participating in shard x_i . If the party maintains (even minimal) information (e.g., the headers of the chain for verification purposes) on the chain of shard x_j , we say that the party is a *light client* for shard x_j .

Lemma 10. *For a robust sharded transaction ledger that requires participants to be light clients on the shards involved in cross-shard transactions, it must hold $\mathbb{E}(s) = o(m)$.*

Theorem 11. *There is no protocol maintaining a robust sharded transaction ledger against an adaptive adversary with $f = \Omega(n/m)$.*

Proof. (Towards contradiction) Suppose there exists a protocol Π that maintains a robust sharded ledger against an adaptive adversary that can corrupt $f = n/m$ parties. From the pigeonhole principle, there exists at least one shard x_i with at most n/m parties (independent of how shards are created). Since the adversary is adaptive, at any round can corrupt all

the parties of shard x_i . In a malicious shard, the adversary can perform arbitrary operations, and thus can spend the same UTXO in multiple cross-shard transactions. However, for a cross-shard transaction to be executed it needs to be accepted by the output shard, which is honest. Now, suppose Π allows the parties of each shard to verify the ledger of another shard. For Lemma 10 to hold, the verification process can affect at most $o(m)$ shards. Note that even a probabilistic verification, i.e., randomly select some transactions to verify, can fail due to storage requirements and the fact that the adversary can perform arbitrarily many attacks. Therefore, for each shard, there are at least 2 different shards ($o(1)$) that do not verify the cross-shard transactions. Thus, the adversary can simply attempt to double-spend the same UTXO across every shard and will succeed in the shards that do not verify the validity of the cross-shard transaction. Hence, consistency is not satisfied. \square

B. Bounds under uniformly random creation of shards

In this section, we assume that the creation of shards is UTXO-dependent; transactions are assigned to shards independently and uniformly at random. This assumption is in sync with the proposed protocols in the literature. In a non-randomized process of creating shards, the adversary can pre-compute and thus bias the process in a permissionless system. Hence, all sharding proposals employ a random process for shard creation. Furthermore, all shards process approximately the same amount of transactions; otherwise the efficiency of the protocol would depend on the shard that processes most transactions. For this reason, we assume the UTXO space is partitioned to shards uniformly at random. Note that we consider UTXOs to be random strings. Under this assumption, we prove all transactions are cross-shard on expectation, and there is no sharding protocol that maintains a robust sharded ledger and requires participants to be light clients on the shards involved in cross-shard transactions.

Lemma 12. *The expected number of cross-shard transactions is $|T|$.*

Lemma 13. *For any protocol that maintains a robust sharded transaction ledger, it holds $s = \Theta(m)$.*

Theorem 14. *There is no protocol that maintains a robust sharded transaction ledger and requires participants to be light clients on the shards involved in cross-shard transactions.*

Proof. Immediately follows from Lemmas 10 and 13. \square

C. Bounds under uniformly random assignment of parties to shards

In this section, we assume parties are assigned to shards uniformly at random. Any other shard assignment strategy yields equivalent or worse guarantees since we have no knowledge on which parties are malicious. Our goal is to upper bound the number of shards for a protocol that maintains a robust sharded transaction ledger in our security model. To satisfy the security properties, we demand each shard to contain at

²Besides checkpoints, other techniques can also be employed to compact a blockchain [12], [13], [22].

least a constant fraction of honest parties $1 - a$ ($< 1 - \frac{f}{n}$). This is due to the limitations of consensus protocols [19].

The size of a shard is the number of the parties assigned to the shard. We say shards are *balanced* if all shards have approximately the same size. We denote by $p = f/n$ the (constant) fraction of the malicious parties. A shard is *a-honest* if at least a fraction of $1 - a$ parties in the shard are honest.

Lemma 15. *Given n parties are assigned uniformly at random to shards and the adversary corrupts at most $f = pn$ parties (p constant), all shards are a -honest (a constant) with high probability $\frac{1}{n^c}$ only if the number of shards is at most $m = \frac{n}{c' \ln n}$, where $c' \geq c \frac{2+a-p}{(a-p)^2}$.*

Corollary 16. *A sharding protocol maintains a robust sharded transaction ledger against an adversary with $f = pn$, only if $m = \frac{n}{c' \ln n}$, where $c' \geq c \frac{5/2-p}{(1/2-p)^2}$.*

Next, we prove that any sharding protocol can scale at most by an $n/\log n$ factor.

Theorem 17. *There is no robust sharded transaction ledger in our security model with scaling factor $\omega = o(\log n)$.*

Proof. In our security model, the adversary can corrupt $f = pn$ parties, p constant. Hence, from Corollary 16, $m = O(\frac{n}{\log n})$. Each party stores at least T/m transactions on average and thus the expected space scaling factor is $\omega_s = n \frac{\Omega(T/m)}{T} = \Omega(\frac{n}{m}) = \Omega(\log n)$. \square

Theorem 18. *There is no protocol that maintains a robust sharded transaction ledger in our security model without verifiable compaction of the state (e.g., checkpoints [18]), for $m > 32 \log n$.*

Proof. (Towards contradiction) Suppose there is a protocol that maintains a robust sharded ledger without checkpoints. To guarantee security against a slowly-adaptive adversary, the protocol re-assigns randomly the parties to shards at the end of each epoch. Hence, at the beginning of each epoch, the parties are required to process a new set of transactions. To check the validity of this new set of transactions, each (honest) shard member downloads and maintains the corresponding ledger. Note that even if the party just maintains the hash-chain of a ledger, it is equivalent to maintaining the list of transactions given that the block size is constant. We will show that after $k > m$ epochs, the expected space scaling factor will be $\Theta(n)$ and thus scalability is not satisfied.

First, we prove that after $k > m$ epochs, each party has been assigned to at least $m/4$ shards. Note that at each epoch the parties are assigned independently and uniformly at random to shards and that each epoch is essentially an independent trial. Thus, after k epochs the probability a party was assigned to one specific shard is $1 - (1 - \frac{1}{m})^k \geq 1 - e^{-\frac{k}{m}} > 1/2$, for $k > m$. Hence, the expected number of shards a party has been assigned to after k epochs is at least $m/2$. By the Chernoff bounds, the probability a party was assigned to less than $m/4$ shards after k epochs is less than $e^{-\frac{m}{4}}$. By the union

bound, the probability every party was assigned to at least $m/4$ different shards after k epochs is at least $1 - ne^{-\frac{m}{4}} > 1 - \frac{1}{n}$, for $m > 32 \log n$.

Now, let us calculate the space scaling factor after k epochs. The input transaction set is $T = \sum_{i=1}^k T_i$. We assume that the number of transactions is equally distributed between epochs hence $T_i = T/k$ for all $i \in \{1, 2, \dots, k\}$. Since the amount of data on each chain grows in time, we assume each party is assigned to a different shard during the first $m/4$ epochs and then the party remains in the same shard (best case regarding storage). At each epoch e , each party stores the entire shard ledger, essentially $\frac{\sum_{i=1}^e T_i}{m}$ transactions. Thus, at epoch $m/4$, the expected storage cost of each party is $\sum_{e=1}^{m/4} \frac{\sum_{i=1}^e T_i}{m}$, which lower bounds the expected storage cost of each party in epoch k . Let $k = m + 4$. Summing over all parties and normalizing over the input, we have the space scaling factor after k epochs at least

$$\frac{n}{T} \sum_{e=1}^{m/4} \frac{\sum_{i=1}^e T_i}{m} = \frac{n}{T} \frac{T}{k} \frac{m+4}{16} = \frac{n}{16} = \Theta(n)$$

\square

IV. EVALUATION OF EXISTING PROTOCOLS

In this section, we evaluate existing sharding protocols with respect to the desired properties defined in Section II-B. A summary of our evaluation can be found in Table I in Appendix B.

The analysis is conducted in the synchronous model and thus any details regarding performance on periods of asynchrony are discarded. The same holds for other practical refinements that do not asymptotically improve the protocols' performance.

A. Elastico

Overview. Elastico is the first distributed blockchain sharding protocol introduced by Luu et al. [20]. The protocol lies in the intersection of traditional BFT protocols and the Nakamoto consensus. The setting is permissionless, and each participant creates a valid identity by producing a proof-of-work (PoW) solution. The adversary controls at most $f < \frac{n}{4}$ computational power. The setting is static and the adversary slowly-adaptive (as described in Section II). The protocol is synchronous (fixed expected delay) and proceeds in epochs.

At the beginning of each epoch, participants are partitioned into small shards (committees) of constant size c . The number of shards is $m = 2^s$, where s is a small constant such that $n = c \cdot 2^s$. A shard member contacts its directory committee to identify the other members of the same shard. For each party, the directory committee consists of the first c identities created in the epoch in the party's view. Transactions are randomly partitioned in disjoint sets based on the hash of the transaction input (in a UTXO model); hence each shard only processes a fraction of the total transactions in the system. The shard members execute a BFT protocol to validate the shard's transactions and then send the validated transactions

to the final committee. The final committee consists of all members with a fixed s -bit shards identity, and is in charge of two operations: (i) computing and broadcasting the final block, which is a digital signature on the union of all valid received transactions³ (via executing a BFT protocol), and (ii) generating and broadcasting a bounded exponential biased random string which is used as a public source of randomness in the next epoch (e.g., for the PoW).

a) Randomness: In each epoch, the final committee (of size c) generates a set of random strings R via a commit-and-XOR protocol. First, all committee members generate an r -bit random string r_i and send the hash $h(r_i)$ to all other committee members. Then, the committee runs an interactive consistency protocol to agree on a single set of hash values S , which they include on the final block. Later, each (honest) committee member broadcasts its random string r_i to all parties in the network. Each party chooses and XORs $c/2+1$ random strings for which the corresponding hash exists in S . The output string is the party's randomness for the epoch. Note that $r > 2\lambda + c - \log(c)/2$, where λ is a security parameter.

b) Assignment to shards: The protocol assigns each identity, created via the PoW Sybil-resistance mechanism, to a random shard in 2^s , identified by an s -bit shard identity.

c) Cross-shard transactions: Each transaction is assigned to a shard according to the hash of the transaction's inputs. Every party maintains the entire blockchain, thus each shard can validate the assigned transaction independently, i.e., there are no cross-shard transactions.

d) Consensus: Elastico does not specify the consensus protocol, but instead can employ any standard BFT protocol, like PBFT [7].

e) Epoch transition: At the end of each epoch, the final committee broadcasts the final block that contains the Merkle hash root of every block of all shards' block. The final block is stored by all parties in the system. Hence when the parties are re-assigned to new shards they already have the hash-chain to confirm the shard ledger and future transactions. Essentially, an epoch in Elastico is equivalent to a block generation round.

Analysis. Elastico's threat model allows for adversaries that can drop or modify messages, and send different messages to honest parties, which is not allowed in our model. However, we show that even under a more restrictive adversarial model, Elastico fails to meet the desired sharding properties. Specifically, we prove Elastico does not satisfy *scalability* and *consistency*. From the security analysis of [20], it follows that persistence and liveness are satisfied in Elastico.

Theorem 19. *Elastico does not satisfy consistency.*

Proof. Suppose a party submits two valid transactions one spending input x and another spending input x and input y . Note that the second is a single transaction with two inputs. In this case, the probability that both hashes (transactions),

³Elastico broadcasts only the Merkle hash root for each block. However, this is asymptotically equivalent to including all transactions since the block size is considered constant.

$H(x, y)$ and $H(x)$, land in the same shard is $1/m$. Hence, the probability of a successful double-spending in a set of T transactions is almost $1 - (1/m)^T$, which converges to 0 as T grows, for any value $m > 1$. However, $m > 1$ is necessary to satisfy scalability (Theorem 9). Therefore, there will be almost surely a round in which two parties report two conflicting transactions and thus consistency is not satisfied. \square

Lemma 20. *The space scaling factor of Elastico is $\omega_s = \Theta(n)$.*

Proof. At the end of each epoch, the final committee broadcasts the final block to the entire network. All parties store the final block, hence all parties maintain the entire input set of transactions. Note that we consider the block size to be constant, thus maintaining the hash-chain for each shard is equivalent to maintaining all the shards' ledgers. It follows that $\omega_s = \Theta(n)$, regardless of the input set T . \square

Theorem 21. *Elastico does not satisfy scalability.*

Proof. Immediately follows from Definition 4 and Lemma 20. \square

B. Monoxide

Overview. Monoxide [32] is an asynchronous proof-of-work protocol, where the adversary controls at most 50% of the computational power of the system. The protocol uniformly partitions the space of user addresses into shards (zones) according to the first k bits. Every party is permanently assigned to a shard uniformly at random. Each shard employs GHOST [28] as the consensus protocol.

Participants are either full-nodes, that verify and maintain the transaction ledgers, or miners investing computational power (hash power) to solve PoW puzzles for profit in addition to being full-nodes. Monoxide introduces a new mining algorithm, called Chu-ko-nu, that enables miners to mine in parallel for all shards. The Chu-ko-nu algorithm aims to distribute the hashing power to protect individual shards from an adversarial takeover. Successful miners include transactions in blocks. A block in Monoxide is divided into two parts: the chaining block that includes all metadata (Merkle root, nonce for PoW, etc.) and creates the hash-chain, and the transaction-block that includes the list of transactions. All parties maintain the hash-chain of every shard in the system.

Furthermore, all parties maintain a distributed hash table (DHT) for peer discovery and identifying parties in a specific shard. This way the parties of the same shard can identify each other and cross-shard transactions are sent directly to the destination shard. Cross-shard transactions are validated in the shard of the payer and verified from the shard of the payee via a relay transaction and the hash-chain of the payer's shard.

a) Randomness: The protocol uses deterministic randomness (e.g., hash function) and does not require any random source.

b) Assignment to shards: Every party is permanently assigned to a shard uniformly at random according the first k bits of its address.

c) *Cross-shard transactions*: An input shard is a shard that corresponds to the address of a sender (payer) while an output shard one that corresponds to the address of a receiver (payee). Each cross-shard transaction is processed in the input shard, where an additional relay transaction is created and included in a block. The relay transaction consists of all metadata needed to verify the validity of the original transaction by only maintaining the hash-chain of a shard (i.e. for light clients). The miner of the output shard verifies that the relay transaction is stable and then includes it in a block in the output shard. Note that in case of forks in the input shard, Monoxide allows to invalidate the relay transactions and rewrite the affected transaction ledgers, to maintain consistency.

d) *Consensus*: The consensus protocol of each shard is GHOST [28]. GHOST is a DAG-based consensus protocol similar to the Nakamoto consensus [23], where the consensus rule is the heaviest subtree instead of the longest chain.

e) *Sybil-resistance*: In a typical PoW election scheme, the adversary can create many identities and target its computational power to specific shards to gain more than half of the hashing power of the shard. In such a case, the security of the protocol fails (both persistence and consistency properties do not hold). To address this issue, Monoxide introduces a new mining algorithm, Chu-ko-nu, that allows parallel mining on all shards. Specifically, a miner can batch valid transactions from all shards and use the root of the Merkle tree of the list of chaining headers in the batch as input to the hash, alongside with the nonce (and some configuration data). Thus, when a miner successfully computes a hash lower than the target, the miner adds a block to every shard.

Analysis. We prove that Monoxide satisfies persistence, liveness, and consistency, but does not satisfy scalability. Note that Theorem 14 also implies that Monoxide does not satisfy scalability since Monoxide demands each party to verify cross-shard transactions by acting as a light client to all shards.

Theorem 22. *Monoxide satisfies persistence and liveness.*

Theorem 23. *Monoxide satisfies consistency.*

Note that allowing to rewrite the transaction ledgers in case a relay transaction is invalidated strengthens the consistency property but weakens the persistence and liveness properties.

Intuitively, to satisfy persistence in a sharded PoW system, the adversarial power needs to be distributed across shards. To that end, Monoxide employs a new mining algorithm, Chu-ko-nu, that incentivizes honest parties to mine in parallel on all shards. However, this implies that a miner needs to verify transactions on all shards and maintain a transaction ledger for all shards. Hence, the verification and space scaling factors are proportional to the number of (honest) participants and the protocol does not satisfy scalability.

Theorem 24. *Monoxide does not satisfy scalability.*

Proof. Let m denote the number of shards (zones), m_p the

fraction of mining power running the Chu-ko-nu mining algorithm and m_d the rest of the mining power ($m_p + m_d = 1$). Additionally, suppose m_s denotes the mining power of one shard. The Chu-ko-nu algorithm enforces the parties to verify transactions that belong to all shards, hence the parties store all sharded ledgers. To satisfy scalability, the space scaling factor of Monoxide can be at most $o(n)$. Thus, at most $o(n)$ parties can run the Chu-ko-nu mining algorithm, hence $nm_p = o(n)$. We note that the adversary will not participate in the Chu-ko-nu mining algorithm as distributing the hashing power is to the adversary's disadvantage.

To satisfy persistence, every shard running the GHOST protocol [28] must satisfy the common prefix property. Thus, the adversary cannot control more than $m_a < m_s/2$ hash power, where $m_s = \frac{m_d}{m} + m_p$. Thus, we have $m_a < \frac{m_d}{2(m_d + m_p)} = \frac{1}{2} - \frac{m_d(m-1)}{2m(m_d + m_p)}$. For n sufficiently large, m_p converges to 0; hence $m_a < \frac{1}{2} - \frac{(m-1)}{2m} = \frac{1}{2m}$. From Theorem 9, $m = \omega(1)$, thus $m_a < 0$ for sufficiently large n . Therefore, Monoxide does not satisfy scalability in our security model. \square

C. OmniLedger

Overview. OmniLedger [18] proceeds in epochs, assumes a partially synchronous model within each epoch (to be responsive), synchronous communication channels between honest parties (with a large maximum delay), and a slowly-adaptive computationally-bounded adversary that can corrupt up to $f < n/4$ parties.

The protocol bootstraps using techniques from ByzCoin [16]. The core idea is that there is a global identity blockchain that is extended once per epoch with Sybil resistant proofs (Proof-of-Work, Proof-of-Stake, or Proof-of-Personhood [5]) coupled with public keys. Then at the beginning of the epoch a sliding window mechanism is employed which defines the eligible validators to be the ones with identities in the last W blocks where W depends on the adaptivity of the adversary. For our definition of slowly adaptive, we set $W = 1$. The UTXO space is partitioned uniformly at random into m shards, each shard maintaining its own ledger.

At the beginning of each epoch, a new common random value is created via a distributed-randomness generation protocol. This protocol employs a VRF-based leader election algorithm to elect a leader who runs RandHound [30] to create the random value. The random value is used as a challenge for the next epoch's identity registration and as a seed to assigning identities of the current epoch into shards.

Once the participants for this epoch are assigned to shards and bootstrap their internal states they start validating transactions and updating the shard's transaction ledger by operating ByzCoinX, a modification of ByzCoin [16]. When a transaction is cross-shard, *Atomix*, a protocol that ensures the atomic operation of transactions across shards is employed. Atomix is a client-driven atomic commit protocol secure against Byzantine adversaries.

a) *Randomness*: The protocol to produce unbiased randomness has two steps. On the first step, all parties evaluate

a Verifiable Random Function using their private key and the randomness of the previous round to generate a “lottery ticket”. Then the parties broadcast their ticket and wait for Δ to be sure that they receive the ticket with the lowest value whose generator is elected as the leader of RandHound.

This second step is a partially-synchronous randomness generation protocol, meaning that even in the presence of asynchrony the safety is not violated. If the leader is honest, then eventually the parties will output an unbiased random value, whereas if the leader is dishonest then there is no liveness. To recover from this type of fault the parties can view-change the leader and go back to the first step in order to elect a new leader.

This composition of randomness generation protocols (leader election and multiparty generation) guarantees that all parties agree on the final randomness (due to the view-change) and the protocol remains safe in asynchrony. Furthermore, if the assumed synchrony bound (which can be increasing like PBFT [7]) is correct, then a good leader will be elected in a constant number of rounds.

Note, however, that the DRG protocol is modular, thus any other scalable distributed-randomness generation protocol with similar guarantees, such as Hydrand [26] or Scrape [6], can be employed.

b) Assignment to shards: Once the parties generate the randomness, each party can independently compute the shard it should start validating this epoch by permuting ($\text{mod } n$) the list of validators (available in the identity chain).

c) Cross-shard transactions (Atomix): The protocol is an adaptation of two-phase commit running with the assumption that the underlying shards are correct and never crash. This assumption is satisfied because of the random assignment and the Byzantine fault-tolerant consensus every shard runs.

Atomix works in two steps: First, the client that wants the transaction to go through requests a proof-of-acceptance or proof-of-rejection from the shards managing the inputs, who log the transactions in their internal blockchain. Afterwards, the client either collects proof-of-acceptance from all the shards or at least one proof-of-rejection. In the first case, the client communicates the proofs to the output shards, who verify the proofs and finish the transaction by generating the necessary UTXOs. In the second case, the client communicates the proofs to the input shards who revert their state and abort the transaction. Atomix, has a subtle replay attack [29], hence we analyze OmniLedger with the fix proposed.

d) Consensus: OmniLedger suggests the use of a strongly consistent consensus in order to support Atomix. This modular approach means that any consensus protocol [7], [11], [16], [17], [25] works with OmniLedger as long as the deployment setting of OmniLedger respect the limitations of the consensus protocol. In its experimental deployment, OmniLedger uses a variant of ByzCoin [16] called ByzCoinX [17] in order to maintain the scalability of ByzCoin and be robust too. We omit the details of ByzCoinX as it is not relevant to our analysis.

e) Epoch transition: A key component that enables OmniLedger to scale is the epoch transition. At the end of every epoch, the parties run consensus on the state changes and append it in a state-block that points directly to the previous epoch’s state-block. This is a classic technique [7] during reconfiguration events of state-machine replication algorithms called checkpointing. New validators do not replay the actual shard’s ledger but instead, look only at the checkpoints which help them bootstrap faster.

In order to guarantee the continuous operation of the system, the parties’ shards are reconfigured in small batches (at most $1/3$ of the shard size), only after they have finished bootstrapping. If there are any blocks committed after the state-block, the validators replay the state-transitions directly.

Analysis. In this section, we prove OmniLedger maintains a robust sharded transaction ledger, meaning that OmniLedger satisfies persistence, consistency, liveness, and scalability (on expectation). Furthermore, we estimate the efficiency of OmniLedger by providing an upper bound on the throughput factor of the protocol.

Lemma 25. *At the beginning of each epoch, OmniLedger provides an unbiased, unpredictable, common to all parties random value (with overwhelming probability within t rounds).*

Lemma 26. *The distributed randomness generation protocol has $O(\frac{n \log^2 n}{R})$ amortized communication complexity, where R is the number of rounds in an epoch.*

Corollary 27. *All shards will have an expected size n/m .*

Lemma 28. *In each epoch, all shards are $\frac{1}{3}$ -honest for $m \leq \frac{n}{300c \ln n}$, where c is a security parameter.*

Note that the bound is theoretical and holds for a large number of parties since the probability tends to 1 as the number of parties grows. For practical bounds, we refer to the analysis of OmniLedger [18].

Theorem 29. *OmniLedger satisfies persistence.*

Proof. From Lemma 28, each shard has an honest supermajority $\frac{2}{3} \frac{n}{m}$ of participants. Hence, persistence holds by the common prefix property of the consensus protocol of each shard. Specifically, for ByzCoinX, persistence holds for depth parameter $k = 1$ because ByzCoinX guarantees finality. \square

Theorem 30. *OmniLedger satisfies liveness.*

Proof. To estimate the liveness of the protocol, we need to examine all three stages: (i) consensus within each shard, (ii) cross-shard transactions via the Atomix protocol, and (iii) the epoch transition, i.e., the DRG protocol.

From Lemma 28, each shard has an honest supermajority $\frac{2}{3} \frac{n}{m}$ of participants. Hence, by chain growth and chain quality properties of the underlying blockchain protocol liveness holds in this stage (an elaborate proof can be found in [10]).

Atomix guarantees liveness since the protocol's efficiency depends on the consensus of each shard involved in the cross-shard transaction. Note that liveness does not depend on the client's behavior; if the appropriate information or some part of the transaction is not provided in multiple rounds to the parties of the protocol then the liveness property does not guarantee the inclusion of the transaction in the ledger. Furthermore, if some other party wants to continue the process it can collect all necessary information from the ledgers of the shards.

Last, during the epoch transition, the distributed randomness generation protocol provides a common random value with overwhelming probability within t rounds (Lemma 25). Hence, liveness is satisfied in this stage as well. \square

Theorem 31. *OmniLedger satisfies consistency.*

Proof. Each shard is $\frac{1}{3}$ -honest (Lemma 28). Hence, consistency holds within each shard, and the adversary cannot successfully double-spend. Nevertheless, we need to guarantee consistency even when transactions are cross-shard. OmniLedger employs Atomix, a protocol which guarantees cross-shard transactions are atomic. Thus, the adversary cannot validate two conflicting transactions across different shards.

Moreover, the adversary cannot revert the chain of a shard and double-spend an input of the cross-shard transaction after the transaction is accepted in all relevant shards because persistence holds (Theorem 29). Suppose persistence hold with probability p . Then, the probability the adversary breaks consistency in a cross-shard transaction is the probability of successfully double-spending in one of the relevant to the transaction shards, hence $1 - p^v$ where v is the average size of transactions. Since v is constant, consistency holds with high probability, given that persistence holds with high probability. \square

To prove OmniLedger satisfies scalability (on expectation) we need to evaluate the scaling factors in three different stages of the system: (i) intra-shard, during the internal consensus protocol of each shard, (ii) cross-shard, during the execution of cross-shard transactions via the atomic commit protocol Atomix, and (iii) during each epoch change, i.e., when parties execute the distributed randomness generation protocol and when they bootstrap their internal states to the new transaction ledger they are assigned to.

Lemma 32. *The consensus protocol of each shard has expected scaling factor $O(n/m)$.*

Lemma 33. *Atomix has expected scaling factor $O(v\frac{n}{m})$, where v is the average size of transactions.*

Lemma 34. *During epoch transition, the bootstrapping of a party's internal state to a shard's ledger has expected scaling factor $O(\frac{n}{m})$.*

Theorem 35. *OmniLedger satisfies scalability with scaling factor $\omega = O(v\frac{n}{m} + v^2) = O(\log n)$, for v constant.*

Proof. To evaluate the scalability of OmniLedger, we need to calculate the scaling factor at three different stages of the system: (i) the consensus protocol within each shard (ω_a), (ii) the execution of cross-shard transactions - via Atomix or an equivalent atomic-commit protocol (ω_b), and (iii) the epoch transition (ω_c). It holds that $\omega = \max(\omega_a, \omega_b, \omega_c)$.

From Lemma 32, the consensus protocol of each shard has expected scaling factor $\omega_a = O(n/m)$. Moreover, the Atomix protocol has expected scaling factor $O(v\frac{n}{m} + v^2)$ (Lemma 33). As discussed, in section III, we assume the average size of transactions to be constant. In this case, the Atomix protocol has expected scaling factor $O(\frac{n}{m})$.

The epoch transition consists of the randomness generation protocol and the bootstrapping of parties' internal state to the newly assigned shards. For $R = \Omega(\log n)$ number of rounds per epoch, the randomness generation protocol has an expected amortized scaling factor $O(\log n)$ (Lemma 26) while the bootstrapping process has an expected amortized scaling factor of $O(n/m)$ (Lemma 34). Overall, the epoch transition has an expected scaling factor $\omega_c = O(n/m)$.

Overall, we have $\omega = \max(\omega_a, \omega_b, \omega_c) = O(v\frac{n}{m} + v^2) = O(\frac{n}{m}) = O(\log n)$, where the last equation holds from Theorem 9 and Lemma 28. \square

Theorem 36. *In OmniLedger, the throughput factor is $\sigma = \mu \cdot \tau \cdot \frac{m}{v} < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}$.*

The parameter v depends on the input transaction set. The parameters μ, τ, a, p depend on the choice of the consensus protocol. Specifically, μ represents the ratio of honest blocks in the chain of a shard. On the other hand, τ depends on the latency of the consensus protocol, i.e., what is the ratio between the propagation time and the block generation time. Last, a expresses the resilience of the consensus protocol (e.g., $1/3$ for PBFT), while p the fraction of corrupted parties in the system ($f = pn$).

In OmniLedger, the consensus protocol is modular, so we chose to maintain the parameters for a fairer comparison to other sharding protocols.

D. RapidChain

Overview. RapidChain [33] is a synchronous protocol and proceeds in epochs. The adversary is slowly-adaptive, computationally-bounded and corrupts less than $1/3$ of the participants ($f < n/3$).

The protocol bootstraps via a committee election protocol that selects $O(\sqrt{n})$ parties - the root group. The root group generates and distributes a sequence of random bits used to establish the reference committee. The reference committee consists of $O(\log n)$ parties, is re-elected at the end of every epoch, and is responsible for: (i) generating the randomness of the next epoch, (ii) validating the identities of participants for the next epoch, and (iii) the reconfiguration of the shards from one epoch to the next (protects against an adversarial shard takeover).

A party can only participate in an epoch if it solves a PoW puzzle with the previous epoch's randomness, submit the solution to the reference committee and consequently be included in the next reference block. The reference block contains the active parties' identities for the next epoch, their shard assignment, and the next epoch's randomness, and is broadcast by the reference committee at the end of each epoch.

The parties are divided into shards of size $O(\log n)$ (committees). Each shard handles a fraction of the transactions, assigned based on the prefix of the transaction ID. Transactions are sent by external users to an arbitrary number of active (for this epoch) parties. The parties then use an inter-shard routing scheme (based on Kademlia [21]) to send the transactions to the input and output shards, i.e., the shards handling the inputs and outputs of the transaction, respectively.

To process cross-shard transactions, the leader of the output shard creates one additional transaction for every different input shard. Then the leader sends (via the inter-shard routing scheme) these transactions to the corresponding input shards for validation. To validate transactions (i.e., a block), each shard runs a variant of the synchronous consensus of Ren et al. [25] and thus tolerates $1/2$ malicious parties.

At the end of each epoch, the shards are reconfigured according to the participants registered in the new reference block. Specifically, RapidChain uses a bounded version of Cuckoo rule [27]; the reconfiguration protocol adds a new party to a shard uniformly at random, and also moves a constant number of parties from each shard and assigns them to other shards uniformly at random.

a) Randomness: RapidChain uses a verifiable secret sharing (VSS) by Feldman [9] to distributively generate unbiased randomness. At the end of each epoch, the reference committee executes a distributed randomness generation (DRG) protocol to provide the random seed of the next epoch. The same DRG protocol is also executed during bootstrapping to create the root group.

b) Assignment to shards & epoch transition: During bootstrapping, the parties are partitioned independently and uniformly at random in groups of size $O(\sqrt{n})$ with a deterministic random process. Then, each group runs the DRG protocol and creates a (local) random seed. Every node in the group computes the hash of the random seed and its public key. The e (small constant) smallest tickets are elected from each group and gossiped to the other groups, along with at least half the signatures of the group. These elected parties are the root group. The root group then selects the reference committee of size $O(\log n)$, which in turn partitions the parties randomly into shards as follows: each party is mapped to a random position in $[0, 1)$ using a hash function. Then, the range $[0, 1)$ is partitioned into k regions, where k is constant. A shard is the group of parties assigned to $O(\log n)$ regions.

During epoch transition, a constant number of parties can join (or leave) the system. This process is handled by the reference committee which determines the next epoch's shard assignment, given the set of active parties for the epoch. The reference committee divides the shards into two groups

depending on the number of active parties from the previous epoch in each shard; the one with the $m/2$ largest in size shards denoted by A , and the rest denoted by I . Every new node is assigned uniformly at random to a shard in A . Then, a constant number of parties is evicted from each shard and assigned uniformly at random in a shard in I .

c) Cross-shard transactions: For each cross-shard transaction, the leader of the output shard creates one "dummy" transaction for each input UTXO in order to move the transactions' inputs to the output shard, and execute the transaction within the shard. To be specific, assume we have a transaction with two inputs I_1, I_2 and one output O . The leader of the output shard creates three new transactions: tx_1 with input I_1 and output I'_1 , where I'_1 holds the same amount of money with I_1 and belongs to the output shard. tx_2 is created similarly. tx_3 with inputs I'_1 and I'_2 and output O . Then the leader sends tx_1, tx_2 to the input shards respectively. In principle the Output shard is claiming to be a trusted channel [3] (which is guaranteed from the assignment), hence the Input shards should transfer their assets there and then execute the transaction atomically inside the output shard (or abort by returning their asset back to the input shard)

d) Consensus: In each round, each shard randomly picks a leader. The leader creates a block, gossips the block header H (containing the round and the Merkle root) to the members of the shard, and initiates the consensus protocol on H . The consensus protocol consists of four rounds: (1) The leader gossips ($H, propose$), (2) All parties gossip the received header ($H, echo$), (3) The honest parties that received at least two echoes containing a different header gossip ($H', pending$), where H' contains the null Merkle root and the round, (4) Upon receiving $\frac{nf}{m} + 1$ echos of the same and only header, an honest party gossips ($H, accept$) along with the received echoes. To increase the transaction throughput, RapidChain allows new leaders to propose new blocks even if the previous block is not yet accepted by all honest parties.

Analysis. RapidChain does not maintain a robust sharded transaction ledger under our security model since it assumes a weaker adversary. To fairly evaluate the protocol, we weaken our security model and assume the adversary cannot change more than a constant number of malicious parties during an epoch transition. In general, we assume at most a constant number of leave/join requests during an epoch transition. Furthermore, the number of epochs is asymptotically less than polynomial to the number of parties. In this weaker security model, we prove RapidChain maintains a robust sharded transaction ledger, and provide an upper bound on the throughput factor of the protocol.

Note that in cross-shard transactions, the "dummy" transactions that are committed in the shards' ledgers as valid, spend UTXOs that are not signed by the corresponding users. Instead, the original transaction, signed by the users, is provided to the shards to verify the validity of the "dummy" transactions. Hence, the transaction validation rules for the parties change. Furthermore, the protocol that handles cross-

shard transactions has no proof of security against malicious leaders. For analysis purposes, we assume the following holds:

Remark 37. *The protocol that handles cross-shard transactions maintains safety even under a malicious leader (of the output shard). This is necessary only for the liveness of the transaction.*

Lemma 38. *The distributed randomness generation protocol has scaling factor $O(\frac{n}{m})$.*

Lemma 39. *In each epoch, all shards are $\frac{1}{2}$ -honest for $m \leq \frac{n}{78c \ln n}$, where c is a security parameter.*

Lemma 40. *In each epoch, all shards have n/m expected size.*

Theorem 41. *RapidChain satisfies persistence.*

Proof. The consensus protocol in RapidChain achieves safety if the shard has no more than $t < 1/2$ fraction of malicious parties ([33], Theorem 2). Hence, the statement follows from Lemma 39. \square

Theorem 42. *RapidChain satisfies liveness.*

Proof. To estimate the liveness of RapidChain, we need to examine the following three stages: (i) the consensus within each shard, (ii) the protocol that handles cross-shard transactions, and (iii) the epoch transition, i.e., the distributed randomness generation protocol and the reconfiguration of shards.

The consensus protocol in RapidChain achieves liveness if the shard has less than $\frac{n}{2m}$ malicious parties ([33], Theorem 3). Thus, liveness is guaranteed during consensus (Lemma 39).

Furthermore, the final committee is $\frac{1}{2}$ -honest with high probability. Hence, the final committee will route each transaction to the corresponding output shard. We assume transactions will reach all relevant honest parties via a gossip protocol. RapidChain employs IDA-gossip protocol, which guarantees message delivery to all honest parties ([33], Lemma 1 and Lemma 2). From Remark 37, the protocol that handles cross-shard transactions maintains safety even under a malicious leader. Hence, all “dummy” transactions will be created and eventually delivered. Since the consensus protocol within each shard satisfies liveness, the “dummy” transactions of the input shards will become stable. Consequently, the “dummy” transaction of the output shard will become valid and eventually stable (consensus liveness). Thus, the protocol that handles cross-shard transactions satisfies liveness.

During epoch transition, the DRG protocol satisfies liveness [9]. Moreover, the reconfiguration of shards allows only for a constant number of leave/join/move operations and thus terminates in a constant number of rounds. \square

Theorem 43. *RapidChain satisfies consistency.*

Proof. During each epoch, each shard is $\frac{1}{2}$ -honest; hence the adversary cannot double-spend and consistency is satisfied.

Nevertheless, to prove consistency is satisfied across shards, we need to prove that cross-shard transactions are atomic. The protocol that handles cross-shard transactions in RapidChain ensures that the “dummy” transaction of the output shard becomes valid only if all “dummy” transactions are stable in the input shards. If a “dummy” transaction of an input shard is rejected, the “dummy” transaction of the output shard will not be executed, and all the accepted “dummy” transactions will just transfer the value of the input UTXOs to another UTXO that belongs to the output shard. This holds because the protocol maintains safety even under a malicious leader (Remark 37).

Lastly, the adversary cannot revert the chain of a shard and double-spend an input of the cross-shard transaction after the transaction is accepted in all relevant shards because consistency with each shard and persistence (Theorem 29) hold. Suppose persistence hold with probability p . Then, the probability the adversary breaks consistency in a cross-shard transaction is the probability of successfully double-spending in one of the relevant to the transaction shards, hence $1 - p^v$ where v is the average size of transactions. Since v is constant, consistency holds with high probability, given that persistence holds with high probability. \square

Similarly to OmniLedger, to calculate the scaling factor of RapidChain, we need to evaluate the following protocols of the system: the internal consensus process, the cross-shard mechanism, the DRG protocol and the reconfiguration of shards (epoch transition).

Lemma 44. *The consensus protocol of each shard has expected scaling factor $O(n/m)$.*

Lemma 45. *The protocol that handles the cross-shard transactions has expected scaling factor $O(v\frac{n}{m})$, where v is the average size of transactions.*

Lemma 46. *During epoch transition, the reconfiguration of shards has expected scaling factor $O(\frac{n}{m})$.*

Note that for $l > n \log n$ epochs, Theorem 46 does not hold.

Theorem 47. *RapidChain satisfies scalability, with expected scaling factor $\omega = O(v\frac{n}{m}) = O(\log n)$, for v constant.*

Proof. From Lemma 44, the consensus protocol of each shard has expected scaling factor $\omega_a = O(n/m)$. Moreover, the protocol that handles cross-shard transactions has expected scaling factor $O(v\frac{n}{m})$ (Lemma 45). As discussed, in section III, we assume constant average size of transactions; hence the protocol has expected scaling factor $O(\frac{n}{m})$.

The epoch transition consists of the randomness generation protocol and the reconfiguration of shards. Both the DRG protocol and the reconfiguration of shards have expected scaling factor $O(\frac{n}{m})$ (Lemma 38 and Lemma 46).

Overall, the expected scaling factor of RapidChain is $\omega = O(\frac{n}{m}) = O(\log n)$, where the last equation holds for $m = \frac{n}{78c \ln n}$ (Lemma 39). \square

Theorem 48. *In RapidChain, the throughput factor is*

$$\sigma = \mu \cdot \tau \cdot \frac{m}{v} < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}.$$

In RapidChain, the consensus protocol is synchronous and thus not practical. We estimate the throughput factor irrespective of the chosen consensus, to provide a fair comparison to other protocols. We notice that both RapidChain and OmniLedger have the same throughput factor when v is constant.

We provide an example of the throughput factor in case the employed consensus is the one suggested in RapidChain. In this case, we have $a = 1/2$, $p = 1/3$, $\mu = 1/2$ ([33], Theorem 1), and $\tau = 1/8$ (4 rounds are needed to reach consensus for an honest leader, and the leader will be honest every two rounds on expectation.). Note that τ can be improved by allowing the next leader to propose a block even if the previous block is not yet accepted by all honest parties; however, we do not consider this improvement. Hence, for $v = 5$, we have throughput factor

$$\sigma < \frac{1}{2} \cdot \frac{1}{8} \cdot \frac{n}{\ln n} \cdot \frac{(\frac{1}{2} - \frac{1}{3})^2}{2 + \frac{1}{2} - \frac{1}{3}} \cdot \frac{1}{5} = \frac{n}{6240 \ln n}$$

E. Chainspace

Chainspace is a sharding protocol introduced by Al-Bassam et al. [2] that operates in the permissioned model. The main innovation of Chainspace is on the application layer. Specifically, Chainspace presents a sharded, UTXO-based distributed ledger that supports smart contracts. Furthermore, limited privacy is enabled by offloading computation to the clients, who need to only publicly provide zero-knowledge proofs that their computation is correct. Chainspace focuses on specific aspects of sharding; epoch transition or reconfiguration of the protocol is not addressed. Nevertheless, the cross-shard communication protocol called S-BAC is of interest as a building block to secure sharding (Appendix A).

V. SHARDING ESSENTIAL COMPONENTS

In this section, we present the necessary components to design a protocol that maintains a robust sharded transaction ledger. In combination with the bounds provided in Section III, we present the boundaries of secure and efficient sharding protocol design for blockchain systems.

The essential ingredients for a sharding protocol in order to maintain a robust sharded transaction ledger are as follows:

(a) **Sybil-resistance:** Necessary for the permissionless setting. Given the slowly adaptive adversary assumption, the Sybil-resistance mechanism needs to depend on the unknown randomness of the previous epoch. The exact protocol (PoW, Pos, etc.) is indifferent.

(b) **Randomness Generation protocol:** Necessary for any setting and should provide unbiased randomness [6], [9], [26], [30]. Due to the slowly-adaptive adversary assumption, the DRG protocol must be executed once per epoch. The protocol is executed either by a reference committee [33] or by all the parties [18] and its cost can be amortized over the rounds of an epoch.

(c) **Partitioning the transaction space and cross-shard mechanism:** The cross-shard transaction mechanism should provide (just like in database transactions) the ACID properties. Durability and Isolation are provided directly by the blockchains of the shards, hence, the cross-shard transaction protocol should provide Consistency (every transaction that commits produces a semantically valid state) and Atomicity (transactions are committed and aborted atomically - all or nothing). To that end, the limitations from Section III apply for any protocol designed to maintain a robust sharded transaction ledger. We provide a detailed overview of an additional state-of-the-art cross-shard mechanism (S-BAC [2]) in Appendix A.

(d) **Consensus protocol of shards:** The consensus protocol needs to satisfy the properties defined by Garay et al. [10] with the additional requirement that light-client verification can be done with a sublinear proof (to the number of rounds), regardless of the last time the light-client synchronized with the chain.

(e) **Epoch transition:** The epoch transition (under a slowly-adaptive adversary) is a critical and often ignored component. It needs two important functions: First, at the end of the epoch the state size should be summarized such that new parties can bootstrap with minimal effort instead of replaying the transactions, e.g., by using checkpoints (Theorem 18). Second, there needs to be global consensus on the new set of Sybil resistant identities. This consensus needs to make sure that a representative number of proposals come from honest parties, in order to protect from censorship.

VI. RELATED WORK

The Bitcoin backbone protocol [10] was the first to formally define and prove a blockchain protocol, more specifically Bitcoin in a PoW setting. Later, Pass et al. [24] showed that there is no PoW protocol that can be robust under asynchrony. With Ouroboros [15] Kiayias et al. extended the ideas of backbone to the Proof-of-Stake (PoS) setting, where they showed that it is possible to have a robust transaction ledger in a semi-synchronous environment as well [8]. Our work is also extending the backbone framework to define a robust sharded ledger. Furthermore, we analyze existing sharding protocols under our framework.

Recently, a few systemization of knowledge papers on sharding [31] as well as consensus [4] and cross-shard communication [34] which have also discussed part of sharding, have emerged. Unlike these, our focus is not a complete list of existing protocols. Instead, we formally define what a secure and efficient sharded ledger is, and evaluate existing sharding protocols under this lens, by either proving or disproving their claims in our framework.

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APPENDIX

A. S-BAC protocol

S-BAC is a shard-led cross-shard consensus protocol employed by Chainspace, a sharding protocol introduced by Al-Bassam et al. [2] that operates in the permissioned model. In S-BAC, the client submits a transaction to the input shards. Each shard internally runs a BFT protocol to tentatively decide whether to accept or abort the transaction locally and broadcasts its local decision to other shards that take part in the transaction. If the transaction fails locally (i.e., is a double-spend), then the shard generates pre-abort(T), whereas if the transaction succeeds locally the shard generates pre-accept(T) and changes the state of the input to locked. After a shard decides to pre-commit(T), it waits to collect responses from other participating shards, and commits the transaction if all shards respond with pre-accept(T), or aborts the transaction if at least one shard announces pre-abort(T). Once the shards decide, they send their decision (accept(T) or abort(T)) to the client and the output shards. If the decision is accept(T), the output shards generate new 'active' objects and the input shards change the input objects to inactive. If an input shard's decision is abort(T), all input shards unlock the input objects by changing their state to 'active'.

S-BAC, just like Atomix, is susceptible to replay attacks [29]. To address this problem, sequence numbers are added to the transactions, and output shards generate dummy objects during the first phase (pre-commit, pre-abort). More details and security proofs can be found on [29], as well as a hybrid of Atomix and S-BAC called Byzcuit.

B. Comparison of sharding protocols

Table I demonstrates which properties are satisfied by the sharding protocols evaluated in this work under our model as defined in Section II. We further include Chainspace, which maintains a robust sharded transaction ledger but only in the permissioned setting. Specifically, we omit the security proofs for Chainspace since they are either included in [2] or are similar to OmniLedger. We include in the evaluation the “permissionless” property, in addition to the security and efficiency properties, namely persistence, consistency, liveness and scalability.

Further, we note that RapidChain maintains a robust sharded ledger but under a weaker model than the one defined in Section II. To be specific, the protocol only allows a constant number of parties to join or leave and the adversary can at most corrupt a constant number of additional parties with each epoch transition. Another shortcoming of RapidChain is the synchronous consensus mechanism it employs. In case of temporary loss of synchrony in the network, the consensus of cross-shard transactions is vulnerable, and thus consistency might not be satisfied [33].

However, most of these drawbacks can be addressed with simple solutions, such as changing the consensus protocol (trade-off performance with security), replacing the epoch transition process with one similar to OmniLedger, etc. Although OmniLedger maintains a robust sharded ledger in a stronger model (as defined in Section II), RapidChain introduces practical speedups on specific components of the system. These improvements are not asymptotically important – and thus not captured by our framework – but might be significant for the performance of deployed sharding protocols.

C. Limitations of Sharding Protocols

Theorem 9. *In any robust sharded transaction ledger the number of shards (parametrized by n) is $m = \omega(1)$.*

Proof. Suppose there is a protocol that maintains a constant number m of sharded ledgers, denoted by x_1, x_2, \dots, x_m . Let n denote the number of parties and T the number of transactions to be processed (wlog assumed to be valid). A transaction is processed only if it is stable, i.e., it is included deep enough in a ledger (k blocks from the end of the ledger where k a security parameter). Each ledger will include T/m transactions on expectation. Now suppose each party participates in only one ledger (best case), thus broadcasts, verifies and stores the transactions of that ledger only. Hence, every party stores T/m transactions on expectation. The expected space scaling factor is $\omega_s = \sum_{\forall i \in [n]} \sum_{\forall x \in L_i} |x|^{[k]} / |T| = \sum_{\forall x \in L_i} \frac{T}{mT} = \frac{n}{m} = \Theta(n)$. Thus, $\omega = \Omega(n)$ and scalability is not satisfied. \square

Lemma 10. *For a robust sharded transaction ledger that requires participants to be light clients on the shards involved in cross-shard transactions, it must hold $\mathbb{E}(s) = o(m)$.*

Proof. We assumed that every ledger interacts on average with s different ledgers, i.e., the cross-shard transactions involve

s many different shards on expectation. The block size is considered constant, i.e., each block includes at most e transactions, where e is a constant. Thus, each party maintaining a ledger and being a light client to s other ledgers must store on expectation $(1 + \frac{s}{e}) \frac{T}{m}$ information. Hence, the expected space scaling factor is

$$\mathbb{E}(\omega_s) = \sum_{\forall i \in [n]} \sum_{\forall x \in L_i} |x|^{[k]} / |T| = n \frac{(1 + \frac{s}{e}) \frac{T}{m}}{T} = \Theta\left(\frac{sn}{m}\right)$$

where the second equation holds due to linearity of expectation. To satisfy scalability, we demand $\mathbb{E}(\omega_s) = o(n)$, hence $s = o(m)$. \square

Lemma 12. *The expected number of cross-shard transactions is $|T|$.*

Proof. Let Y_i be the random variable that shows if a transaction is cross-shard; $Y_i = 1$ if $tx_i \in T$ is cross-shard, and 0 otherwise. Since UTXOs are assigned to shards uniformly at random, $\Pr[i \in x_k] = \frac{1}{m}$, for all $i \in v$ and $k \in [m] = \{1, 2, \dots, m\}$. The probability that all UTXOs in a transaction $tx \in T$ belong to the same shard is $\frac{1}{m^{v-1}}$ (where v is the number of UTXOs in tx). Hence, $\Pr[Y_i = 1] = 1 - \frac{1}{m^{v-1}}$. Thus, the expected number of cross-shard transactions is $\mathbb{E}(\sum_{\forall tx_i \in T} Y_i) = |T|(1 - \frac{1}{m^{v-1}})$. Since, $m(n) = \omega(1)$ (Theorem 9) and v constant, the expected cross-shard transactions converges to T for n sufficiently large. \square

Lemma 13. *For any protocol that maintains a robust sharded transaction ledger, it holds $s = \Theta(m)$.*

Proof. We assume each transaction has a single input and output, hence $v = 2$. This is the worst-case input for evaluating how many shards interact per transaction; if $v \gg 2$ then each transaction would most probably involve more than two shards and thus each shard would interact with more different shards for the same set of transactions.

For $v = 2$, we can reformulate the problem as a graph problem. Suppose we have a random graph G with m nodes, each representing a shard. Now let an edge between nodes u, w represent a transaction between shards u, w . Note that in this setting we allow self-loops, which represent the intra-shard transactions. We create the graph G with the following random process: We choose an edge independently and uniformly at random from the set of all possible edges including self-loops, denoted by E' . We repeat the process independently $|T|$ times, i.e., as many times as the cardinality of the transaction set. Note that each trial is independent and the edges are chosen uniformly at random due to the corresponding assumptions concerning the transaction set and the shard creation. We show that the average degree of the graph is $\Theta(m)$, which immediately implies the statement of the lemma.

Let the random variable Y_i represent the existence of edge i in the graph, i.e., $Y_i = 1$ if edge i was created at any of the T trials, 0 otherwise. The set of all possible edges in the graph is E , $|E| = \binom{m}{2} = \frac{m(m-1)}{2}$. Note that this is not the same as set E' which includes self-loops and thus $|E'| = \binom{m}{2} +$

TABLE I
SUMMARIZING SHARDING PROTOCOLS UNDER OUR MODEL

Protocol	Persistence	Consistency	Liveness	Scalability	Permissionless
Elastico	✓	✗	✓	✗	✓
Monoxide	✓	✓	✓	✗	✓
OmniLedger	✓	✓	✓	✓	✓
RapidChain	✓	✓	✓	✓	✓
Chainspace	✓	✓	✓	✓	✗

$m = \frac{m(m+1)}{2}$. For any vertex u of G , it holds $\mathbb{E}[\deg(u)] = \frac{2\mathbb{E}[\sum_{i \in E} Y_i]}{m}$, where $\deg(u)$ denotes the degree of node u . We have, $Pr[Y_i = 1] = 1 - Pr[Y_i = 0] = 1 - Pr[Y_i = 0 \text{ at trial } 1]Pr[Y_i = 0 \text{ at trial } 2] \dots Pr[Y_i = 0 \text{ at trial } T] = 1 - \left(1 - \frac{2}{m(m+1)}\right)^{|T|}$. Thus,

$$\begin{aligned}\mathbb{E}[\deg(u)] &= \frac{2m(m-1)}{2} \left[1 - \left(1 - \frac{2}{m(m+1)}\right)^{|T|}\right] \\ &= (m-1) \left[1 - \left(1 - \frac{2}{m(m+1)}\right)^{|T|}\right]\end{aligned}$$

Therefore, for many transactions we have $|T| = \omega(m^2)$ and consequently $\mathbb{E}[\deg(u)] = \Theta(m)$. \square

Lemma 15. *Given n parties are assigned uniformly at random to shards and the adversary corrupts at most $f = pn$ parties (p constant), all shards are a -honest (a constant) with high probability $\frac{1}{n^c}$ only if the number of shards is at most $m = \frac{n}{c' \ln n}$, where $c' \geq c \frac{2+a-p}{(a-p)^2}$.*

Proof. To prove the lemma, it is enough to show that if we only assign the $f = pn$ malicious parties independently and uniformly at random to the m shards, then all shards will have less than $a \frac{n}{m}$ parties.

From this point on, let n denote the malicious parties. We will show that for $m = \frac{n}{c' \ln n}$ and a carefully selected constant c' , all shards will have less than $(1 + (a-p)) \frac{n}{m}$ parties.

Let Y_i denote the size of shard i . Then, $\mathbb{E}[Y_i] = \frac{n}{m}$. By the Chernoff bound, we have

$$Pr\left[Y_i \geq (1 + (a-p)) \frac{n}{m}\right] \leq e^{\frac{(a-p)^2}{2+a-p}} \frac{n}{m}$$

The probability that all shards have less than $(1 + (a-p)) \frac{n}{m}$ parties is given by the union bound on the number of shards,

$$\begin{aligned}p &= 1 - \left(Pr\left[Y_1 \geq (1 + (a-p)) \frac{n}{m}\right] + Pr\left[Y_2 \geq (1 + (a-p)) \frac{n}{m}\right] + \dots + Pr\left[Y_m \geq (1 + (a-p)) \frac{n}{m}\right]\right) \\ \Rightarrow p &\geq 1 - m e^{\frac{(a-p)^2}{2+a-p}} \frac{n}{m} \geq 1 - \frac{1}{n^c}, c > 1\end{aligned}$$

The last inequality holds for $m \leq \frac{n}{c' \ln n}$, $c' \geq c \frac{2+a-p}{(a-p)^2}$, in which case all shards are a -honest with probability $1 - \frac{1}{n^c}$. \square

Corollary 16. *A sharding protocol maintains a robust sharded transaction ledger against an adversary with $f = pn$, only if $m = \frac{n}{c' \ln n}$, where $c' \geq c \frac{5/2-p}{(1/2-p)^2}$.*

Proof. To maintain the security properties, all shards must be a -honest, where a depends on the underlying consensus protocol. To the best of our knowledge, all Byzantine-fault tolerant consensus protocols require at least honest majority to also ensure external verifiability of the consensus' decision, hence $a \leq 1/2$. From Lemma 15, $m = \frac{n}{c' \ln n}$, where $c' \geq c \frac{5/2-p}{(1/2-p)^2}$. \square

D. Monoxide

Theorem 22. *Monoxide satisfies persistence and liveness.*

Proof. From the analysis of Monoxide, it holds that if all honest miners follow the Chu-ko-nu mining algorithm, then honest majority within each shard holds with high probability for any adversary with $f < n/4$ (5.3, [32]).

Assuming honest majority within shards, persistence depends on two factors: the probability a stable transaction becomes invalid in a shard's ledger, and the probability a cross-shard transaction is reverted after being confirmed. Both these factors solely depend on the common prefix property of the shards' consensus mechanism. Monoxide employs GHOST as the consensus mechanism of each shard, hence the common prefix property is satisfied if we assume that invalidating the relay transaction does not affect other shards [14]. Suppose common prefix is satisfied with probability $1 - p$ (which is overwhelming on the "depth" security parameter k). Then, the probability none of the outputs of a transaction are invalidated is $(1 - p)^{(v-1)}$ (worst case where $v - 1$ outputs – relay transactions – link to one input). Thus, a transaction is valid in a shard's ledger after k blocks with probability $(1 - p)^v$, which is overwhelming in k since v is considered constant. Therefore, persistence is satisfied.

Similarly, liveness is satisfied within each shard. Furthermore, this implies liveness is satisfied for cross-shard transactions. In particular, both the initiative and relay transactions will be eventually included in the shards' transaction ledgers, as long as chain quality and chain growth are guaranteed within each shard [14]. \square

Theorem 23. *Monoxide satisfies consistency.*

Proof. The common prefix property is satisfied with high probability in GHOST [15]. Thus, intra-shard transactions satisfy consistency with high probability (on the "depth" security parameter). Furthermore, if a cross-shard transaction output is invalidated after its confirmation, Monoxide allows rewriting the affected transaction ledgers. Hence, consistency

is restored in case of cross-transaction failure. Thus, overall, consistency is satisfied in Monoxide. \square

E. OmniLedger

Lemma 25. *At the beginning of each epoch, OmniLedger provides an unbiased, unpredictable, common to all parties random value (with overwhelming probability within t rounds).*

Proof. The statement holds if the elected leader that orchestrates the distributed randomness generation protocol (RandHound or equivalent) is honest. On the other hand, if the leader is malicious, the leader cannot affect the security of the protocol, meaning the leader cannot bias the random value. However, a malicious leader can delay the process by being unresponsive. We show that there will be an honest leader, hence the protocol will output a random value, with overwhelming probability in the number of rounds t .

The adversary cannot pre-mine PoW puzzles, because the randomness of each epoch is used in the PoW calculation of the next epoch. Hence, the expected number of identities the adversary will control (number of malicious parties) in the next epoch is $f < n/4$. Hence, the adversary will have the smallest ticket - output of the Verifiable Random Function - and thus will be the leader that orchestrates the distributed randomness generation protocol (RandHound) with probability $1/2$. Then, the probability there will be an honest leader in t rounds is $1 - \frac{1}{2^t}$, which is overwhelming in t .

The unpredictability is inherited by the properties of the employed distributed randomness generation protocol. \square

Lemma 26. *The distributed randomness generation protocol has $O(\frac{n \log^2 n}{R})$ amortized communication complexity, where R is the number of rounds in an epoch.*

Proof. The DRG protocol inherits the communication complexity of RandHound, which is $O(c^2 n)$ [26]. In [30], the authors claim that c is constant. However, the protocol requires a constant fraction of honest parties (e.g. $n/3$) in each of the n/c partitions of size c against an adversary that can corrupt a constant fraction of the total number of parties (e.g. $n/4$). Hence, from Lemma 15, we have $c = \Omega(\log n)$, which leads to communication complexity $O(n \log^2 n)$ for each epoch. Assuming each epoch consist of R rounds, the amortized per round communication complexity is $O(\frac{n \log^2 n}{R})$. \square

Corollary 27. *All shards will have an expected size n/m .*

Proof. Due to Lemma 25, the n parties are assigned independently and uniformly at random to m shards. Hence, the expected number of parties in a shard is n/m . \square

Lemma 28. *In each epoch, all shards are $\frac{1}{3}$ -honest for $m \leq \frac{n}{300c \ln n}$, where c is a security parameter.*

Proof. Due to Lemma 25, the n parties are assigned independently and uniformly at random to m shards. Since $a = 1/3 > p = 1/4$, both a, p constant, the statement holds from Lemma 15 for $m = \frac{n}{c' \ln n}$, where $c' > 300c$. \square

Lemma 32. *The consensus protocol of each shard has expected scaling factor $O(n/m)$.*

Proof. From Corollary 27, the expected number of parties in a shard is n/m . ByzCoin has quadratic to the number of parties worst case communication complexity, hence the communication scaling factor of the protocol is $\omega_a = \omega_a = O(n/m)$.

The verification complexity collapses to the communication complexity. The space scaling factor is $O(\frac{n}{m})$, as each party maintains the ledger of the assigned shard for the epoch. \square

Lemma 33. *Atomix has expected scaling factor $O(v \frac{n}{m})$, where v is the average size of transactions.*

Proof. In a cross-shard transaction, Atomix allows the participants of the output shards to verify the validity of the transaction's inputs without maintaining any information on the input shards' ledgers. This holds due to persistence (Theorem 29).

Furthermore, the verification process requires each input shard to verify the validity of the transaction's inputs and produce a proof-of-acceptance or proof-of-rejection. This corresponds to one query to the verification oracle for each input. In addition, each party of an output shard must verify that all proofs-of-acceptance are present and no shard rejected an input of the cross-shard transaction. The proof-of-acceptance (or rejection) consists of the signature of the shard which is linear to the number of parties in the shard. The relevant parties have to receive all the information related to the transaction from the client (or leader), hence the communication scaling factor is $O(v \frac{n}{m})$.

So far, we considered the communication complexity of Atomix. However, each input must be verified within the corresponding input shard. From Lemma 32, we get that the communication scaling factor at this step is $O(v \frac{n}{m})$. Thus, the overall scaling factor of Atomix is $O(v \frac{n}{m})$. \square

Lemma 34. *During epoch transition, the bootstrapping of a party's internal state to a shard's ledger has expected scaling factor $O(\frac{n}{m})$.*

Proof. During the epoch transition each party is assigned to a shard u.a.r. and thus most probably needs to bootstrap to a new shard, meaning the party must store the new shard's ledger. At this point, within each shard OmniLedger introduces checkpoints, the state blocks that summarize the state of the ledger. Therefore, when a party syncs with a shard's ledger, it does not store the entire ledger but only the active UTXO pool corresponding to the previous epoch's state block.

Let us calculate the space scaling factor after e epochs. The input transactions set is $T = \sum_{i=1}^e T_i$. For any party of the protocol the expected storage cost at each epoch i is T_i/m . Hence, at epoch e , the expected storage cost of a party is $\sum_{i=1}^e \frac{T_i}{m}$. Summing over all parties and normalizing over the input, we have the space scaling factor $\frac{n}{T} \sum_{i=1}^e \frac{T_i}{m} = \frac{nT}{mT} = \frac{n}{m}$. Note that the scaling factor remains the same even if we take into account the slow mitigation of parties proposed in OmniLedger to maintain operability during the epoch transition. This is because each party can maintain at

most two ledgers in parallel at this stage, which does not affect the asymptotic space scaling factor.

There is no verification process during this stage. Furthermore, each party that is reassigned in a new shard must receive the state block of the new shard by $O(n/m)$ parties for security reasons. Thus, the communication complexity of the protocol is $O(\frac{n \log n}{R})$ amortized per round, where R is the number of rounds in an epoch. Hence, for $R = \Omega(\log n)$ number of rounds in each epoch, the expected communication scaling factor (amortized per round) is constant. Therefore, the space scaling factor is dominant during this phase, and the overall scaling factor is $O(n/m)$. \square

Theorem 36. *In OmniLedger, the throughput factor is $\sigma = \mu \cdot \tau \cdot \frac{m}{v} < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}$.*

Proof. In Atomix, at most v shards are affected per transaction, therefore $m' < m/v^4$. From Lemma 15, $m < \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p}$. Therefore, $\sigma < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}$. \square

F. RapidChain

Lemma 38. *The distributed randomness generation protocol has scaling factor $O(\frac{n}{m})$.*

Proof. The DRG protocol is executed by the final committee once each epoch. The size of the final committee is $O(\log n)$. The communication complexity of the DRG protocol is quadratic to the number of parties [9]. Thus, the communication scaling factor is $O(n/m)$. \square

Lemma 39. *In each epoch, all shards are $\frac{1}{2}$ -honest for $m \leq \frac{n}{78c \ln n}$, where c is a security parameter.*

Proof. During the RapidChain bootstrapping protocol (first epoch), the n parties are partitioned independently and uniformly at random into m shards [9]. For $p = 1/3$, the shards are $\frac{1}{2}$ -honest only if $m \leq \frac{n}{78c \ln n}$, where c is a security parameter (Lemma 15). At any time during the protocol, all shards remain $\frac{1}{2}$ -honest (Theorem 5, [33]). Hence, the statement holds after each epoch transition, as long as the number of epochs is $o(n)$. \square

Lemma 40. *In each epoch, all shards have n/m expected size.*

Proof. During the RapidChain bootstrapping protocol (first epoch), the n parties are partitioned independently and uniformly at random into m shards [9]. The expected shard size in the first epoch is n/m . Furthermore, during epoch transition the shards remain “balanced” (Theorem 5, [33]), i.e., the size of each shard is $O(n/m)$. \square

Lemma 44. *The consensus protocol of each shard has expected scaling factor $O(n/m)$.*

⁴If v is not constant, a more elaborate analysis might yield a lower upper bound on m' that m/v . However, if v approximates the number of shards m , then m is also bounded by the scalability of the Atomix protocol (Lemma 33), thus the throughput factor can be significantly lower.

Proof. From Lemma 40, the expected number of parties in a shard is $O(n/m)$. The consensus protocol of RapidChain has quadratic to the number of parties communication complexity. Hence, the communication scaling factor of the protocol is $\omega_a = \omega_o = O(n/m)$.

The verification complexity collapses to the communication complexity. The space scaling factor is $O(\frac{n}{m})$, as each party maintains the ledger of the assigned shard for the epoch. \square

Lemma 45. *The protocol that handles the cross-shard transactions has expected scaling factor $O(v \frac{n}{m})$, where v is the average size of transactions.*

Proof. During the execution of the protocol, the interaction between the input and output shards is limited to the leader, who creates and routes the “dummy” transactions. Hence, the communication complexity of the protocol is dominated by the consensus within the shards. For an average size of transactions v , the communication scaling factor is $O(vn/m + v) = O(vn/m)$ (Lemma 40). Note that this bound holds for the worst case, where transactions have $v - 1$ inputs and a single output while all UTXOs belong to different shards.

For each cross-shard transaction, each party of the input and output shards queries the verification oracle once. Hence, the verification scaling factor is $O(vn/m)$. Last, the protocol does not require any verification across-shards and thus the only storage requirement for each party is to maintain the ledger of the shard it is assigned to.

Overall, the scaling factor of the protocol is $O(vn/m)$. \square

Lemma 46. *During epoch transition, the reconfiguration of shards has expected scaling factor $O(\frac{n}{m})$.*

Proof. The number of join/leave and move operations is constant per epoch, denoted by k . Further, each shard is $\frac{1}{2}$ -honest (Lemma 39) and has size $O(\frac{n}{m})$ (Lemma 40); these guarantees hold as long as the number of epochs is $o(n)$.

To determine the space scaling factor of the reconfiguration across l epochs, we need to estimate the expected number of different shards each party has been assigned to during these epochs. We will show that the expected number of ledgers each party needs to maintain is constant even for $l = n$ epochs.

The probability a party has not been assigned to a specific shard is $(1 - \frac{k}{mn})^l \approx 1 - e^{-\frac{kl}{nm}} = 1 - e^{-\frac{k}{m}}$. The expected number of shards a party has been to after l epochs is $m(1 - e^{-\frac{k}{m}}) \leq m \frac{k}{m} = k$ which is constant. Thus, the space scaling factor is $k \frac{n}{m} = O(\frac{n}{m})$. \square

Theorem 48. *In RapidChain, the throughput factor is*

$$\sigma = \mu \cdot \tau \cdot \frac{m}{v} < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}.$$

Proof. In RapidChain, at most v shards are affected per transaction – when each transaction has $v - 1$ inputs and one output, and all belong to different shards. Therefore, $m' < m/v$. From Lemma 15, $m < \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p}$. Therefore, $\sigma < \mu \cdot \tau \cdot \frac{n}{\ln n} \cdot \frac{(a-p)^2}{2+a-p} \cdot \frac{1}{v}$. \square