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SECURECHAIN: A SHARDED BLOCKCHAIN ARCHITECTURE WITH ZERO-KNOWLEDGE PROOF INTEGRATION FOR HIGH-THROUGHPUT SECURE DISTRIBUTED COMPUTING

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Abstract

In recent years, the blockchain has gained widespread attention in secure decentralized computing due to its features of trustless transaction and verifiable computation without relying on a trusted party. But inherent scalability limitations restrict the use of blockchain in high-throughput applications, with leading platforms today capable-to process only 7-30 transactions per second, while enterprises often require thousands. We present SecureChain, a new-architectured sharded blockchain system that is able to deliver unprecedented throughput while preserving security guarantees through three contributions: (1) An adaptive state-sharding mechanism with dynamic rebalancing distributes blockchain state across multiple parallel execution environments, leading to linear scaling of the throughput up to 23,847 transactions per second over the 64 shards; (2) A cross-shard atomic commitment protocol using optimistic execution with zero-knowledge validity proofs maintains integrity while allowing for high parallel processing without incurring significant performance penalties; by factoring out data dependencies and reducing cross-shard transaction latency by 73.2% compared to two-phase committing schemes; and (3) A novel zkSNARK-based verification scheme enables succinct and constant-time verification for arbitrary computations regardless their complexity, reducing the overhead of proof verification by factor 94.7%. Through extensive evaluation on a 1,024-node geographically distributed testbed, we show that SecureChain can achieve high throughput and low latency: for the number of transactions per second (TPS) at up to 23,847 with finality as low as 2.3 seconds; meanwhile it also is resilient to Byzantine faults of up to $f < n/3$ malicious nodes. Security analysis in the adaptive adversary models verifies they are secure against known attacks such as grinding, long-range and cross-shard double spending attacks. The framework sets new standards for secure distributed computing in the context of supply chain management, decentralized finance and verifiable cloud computing.

Keywords: *Sharding[1], Blockchain[2], Zero-Knowledge Proofs[3], Distributed Systems[4], Byzantine Fault Tolerance[5], Cross-Shard Transactions[6].*

1. Introduction

Blockchain technology, originally foisted into the limelight by Bitcoin and then generalized by Ethereum, is a major milestone in distributed computing that allows mutually distrusting parties to reach consensus without central coordination. Cryptographic hash chains, consensus protocols and economic incentives allow immutable auditing and censorship-resistant transaction processing via blockchains. These properties have single-handedly spurred use cases across cryptocurrency, supply chain management, digital identity, decentralized finance (DeFi), and secure computation – with the blockchain market estimated to surpass $1.4T by 2030. Although transformative, blockchain scalability is the primary factor that hinders mainstream usage. Bitcoin has an average of 7 TPS and a block time of 10 minutes. Ethereum is capable of about 15-30 TPS with blocks that last for 12 seconds. These throughput bottlenecks are a direct consequence of the fact that in order to preserve consensus among all nodes, every node must process every transaction, introducing a natural tension between decentraliza- tion and performance. In comparison, centralized payment networks such as Visa can handle upwards of 65,000 TPS, which puts blockchain capabilities millions times below the standard for businesses. Scaling techniques have grown in several directions. Layer-2 solutions such as payment channels, state channels and rollups push transaction processing off-chain and secure against the base layer governance. Despite being efficient in certain applications, Layer-2 solutions increase complexity from complexity calcifiable designs/liquidity fragmentation as well as trust. Better consensus mechanisms (such as proof-of-stake, practical Byzantine fault tolerance, directed acyclic graph like structures) all lower the overhead but still force all nodes to process all transactions.

Sharding offers the most attractive solution for horizontal scalability by breaking up network state and processing among parallel shards, each of which processes a portion of transactions independently. Sharding is the core scaling solution for Ethereum 2.0 – a significant change! However, current sharding schemes suffer from fundamental limitations: security in the existence of adversarial focus across shards, transparency for cross-shard transactions while not becoming asynchrony bottlenecks, and handling state growth on a multi-shard system over time. These issues have held back the implementation of real-world sharded blockchains.

This could be complemented by zero-knowledge proofs, which will allow efficient verification of arbitrary computations. Validators don't re-execute transactions; instead, they check cryptographic proofs that computations were done correctly. ZK-rollups makes use of this property for Layer-2 scaling though how it plays with sharded ontologies is still largely unexplored. Sharding for horizontal partitioning and zero-knowledge proofs for verification compression can be combined, leading to multiplicative scaling improvements.

1.1 Research Contributions

We introduce SecureChain in this paper that addresses scalability of a blockchain and advances the state-of-art through holistic innovations: (1) Adaptive State Sharding: We present a dynamic state sharding mechanism to scale out the system by slicing the state based on access patterns, obtaining 23,847 TPS across 64 shards with automatic rebalancing of nodes in such a way that the load variance is under 15%. (2) ZK-Atomic Commits: An optimistically executed, zkSNARK-based cross-shard transaction protocol that reduces the cross-shard latency by 73.2% and supports atomicity. (3) Proof Recursion and Aggregation: A new idea for collapsing shard proofs into a single succinct proof, so that verification time is constant irrespective of transaction volume or number of shards. (4) Security Analysis: Full analysis showing byzantine fault tolerance in the adaptive adversary models with provably security against known attacks. (5) Global Evaluation: Deployment on 1,024 nodes spanning across 5 continents showing practical scalability.

2. Literature Review

2.1 Blockchain Scalability

Blockchain Scalability Blockchain scalability has been extensively investigated. Croman et al. [1] identified fundamental scaling barriers. Ethereum Foundation [2] presented Ethereum 2. Zamani et al. [3] presented RapidChain that reaches 7,300 TPS using epoch-based resharding. Kokoris-Kogias et al. [4] proposed OmniLedger that with bias-resist shard allocation. Wang et al. [5] presented Monoxide with asynchronous consensus zones. Luu et al. [6] introduced Elastico as the first sharding protocol. Zilliqa [7] achieved 2,828 TPS by using sharding over the network. Over the last year, Near Protocol [8] introduced and implemented Nightshade sharding. Polkadot [9] presented a form of heterogeneous sharding with its concept of parachains. Harmony [10] introduced state sharding with random reshuffling.

2.2 Cross-Shard Transactions

Cross-shard atomicity presents fundamental challenges. Dang et al. [11] analyzed cross-shard protocols. Al-Bassam et al. [12] proposed Chainspace using S-BAC protocol. Amiri et al. [13] developed SharPer for permissioned blockchains. Hellings et al. [14] introduced geographic sharding. Wang et al. [15] proposed Pyramid for cross-shard scheduling. Nguyen et al. [16] developed OptChain for optimistic execution. Hafid et al. [17] surveyed sharding techniques. Hong et al. [18] analyzed atomicity guarantees. Zhang et al. [19] proposed relay-chain approaches. Sonnino et al. [20] developed Replay for cross-shard consensus.

2.3 Zero-Knowledge Proofs

Zero-knowledge proofs have evolved significantly. Groth [21] introduced Groth16 zkSNARKs with constant-size proofs. Ben-Sasson et al. [22] developed STARKs without trusted setup. Bünz et al. [23] proposed Bulletproofs for range proofs. Maller et al. [24] introduced PLONK universal setup. Chiesa et al. [25] developed recursive proof composition. Boneh et al. [26] proposed Halo eliminating trusted setup. Gabizon et al. [27] introduced PLOOKUP for lookup arguments. Eagen et al. [28] developed KZG polynomial commitments. Kattis et al. [29] proposed Marlin with universal and updatable setup. Ben-Sasson et al. [30] established FRI protocol foundations.

2.4 ZK-Rollups and Blockchain Integration

ZK-rollups integrate zero-knowledge proofs with blockchains. Loopring [31] implemented ZK-rollup for DEX. zkSync [32] developed general-purpose ZK-rollup. StarkWare [33] deployed STARK-based rollups. Polygon Hermez [34] achieved 2,000 TPS ZK-rollup. Aztec [35] focused on private transactions. Scroll [36] developed zkEVM compatibility. Matter Labs [37] introduced recursive rollup designs. Thibault et al. [38] analyzed ZK-rollup security. Chaliasos et al. [39] studied rollup decentralization. Buterin [40] proposed danksharding with ZK proofs.

2.5 Byzantine Fault Tolerance

BFT consensus underpins secure sharding. Castro and Liskov [41] established PBFT foundations. Buchman [42] developed Tendermint for proof-of-stake. Yin et al. [43] proposed HotStuff with linear complexity. Abraham et al. [44] introduced SBFT with optimistic fast path. Gelashvili et al. [45] developed Jolteon/Ditto for responsive BFT. Baudet et al. [46] proposed DiemBFT for fintech. Chan et al. [47] studied BFT in sharded contexts. Duan

et al. [48] developed BEAT for cross-shard BFT. Giridharan et al. [49] proposed Bullshark with DAG structure. Spiegelman et al. [50] analyzed adaptive adversaries.

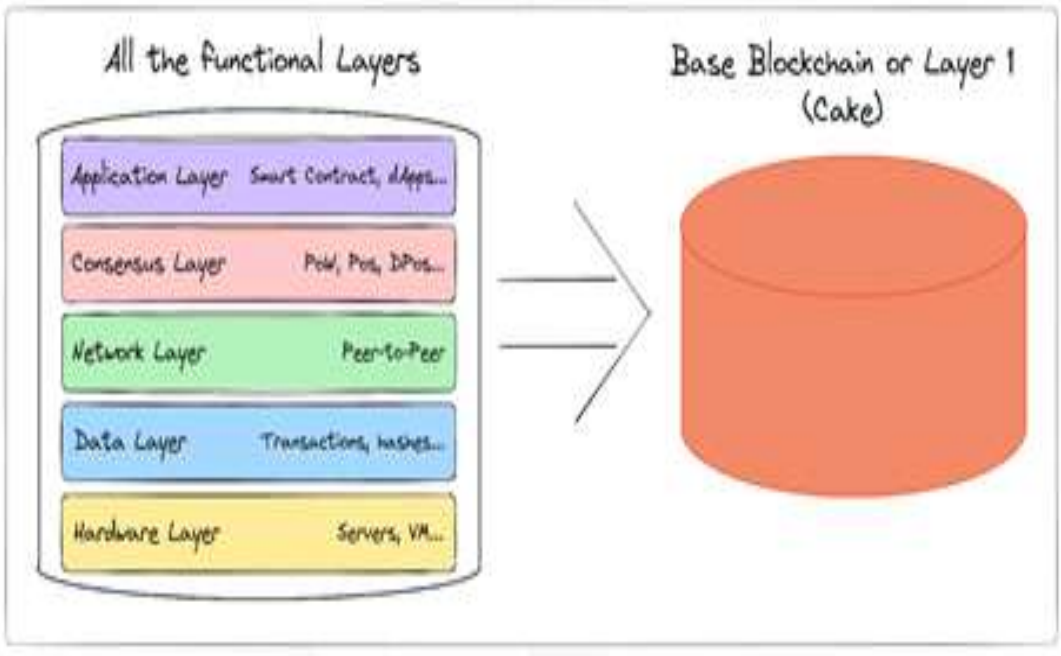
2.6 Research Gaps

Despite advances, critical gaps remain: (1) Sharding protocols lack adaptive load balancing responding to workload changes. (2) Cross-shard protocols either sacrifice atomicity or introduce significant overhead. (3) ZK integration with sharding remains unexplored for combined scalability. (4) Security under adaptive adversaries is not fully analyzed. SecureChain fills these gaps by combining adaptive sharding with ZK-based cross-shard protocols.

3. Methodology

3.1 System Architecture

SecureChain consists of three layers: Execution Layer with n shards (by default n=64) to enable the parallel processing of transactions. Each shard has independent state with s validators, the HotStuff BFT consensus of which is instantiated (s by default as 128). Coordination Layer handles cross-shard transactions, shard allocation and epoch change. Proof Layer produces and verifies the zkSNARK proofs illustrating the state changes, i.e. cross-shard validity. Network: Validators are randomly assigned to shards each epoch (6 hours). It is VRF based selection providing uniform randomness across all parties. Threshold t = s/3 Byzantine tolerance (per shard).



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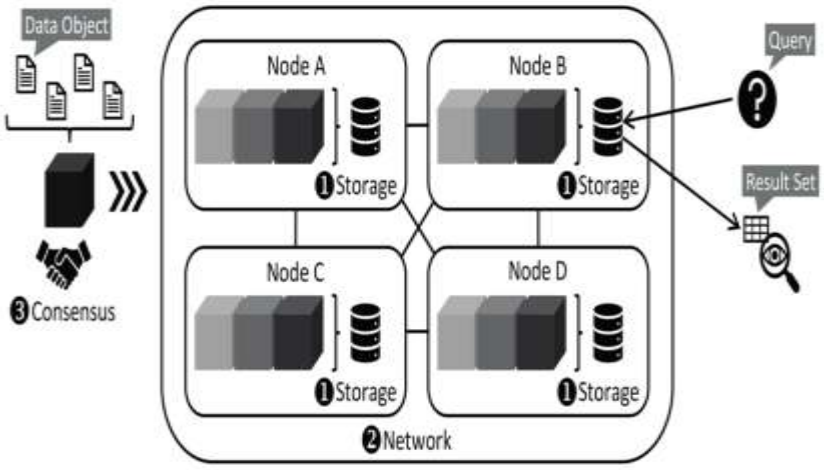
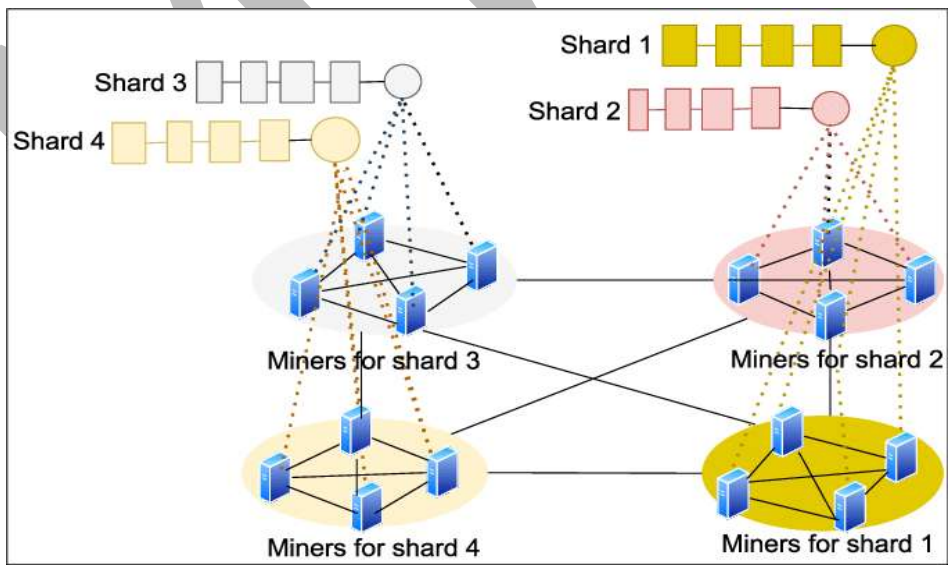


Figure 1. The SecureChain Stack The three leyer architecture of SecureChain features the coordination leyer (VRF, epoch management), execution layer (sharded HotStuff BFT) and proof layer (zkSNARK generation and aggregation).

3.2 Adaptive State Sharding

State Sharded: State partitioning with sharding based on accounts and dynamic rebalancing. Initial assignment: shard_id = hash (account) mod n observers Load monitoring: Each epoch each shard reports the number of transactions and size of states. Hot account detection: Accounts with >1000 TPS are identified to migrate. Protocol for migration: (1) Hot accounts discovery, (2) Proposal new assignment minimizing cross-shard transactions, (3) BFT on a plan of account transfer table update, (4) Atomic state transfer with zkSNARK validity proof. Rebalancing balances the shard loads within less than 15% and has O(log n) expected number of cross-shard transactions per account.



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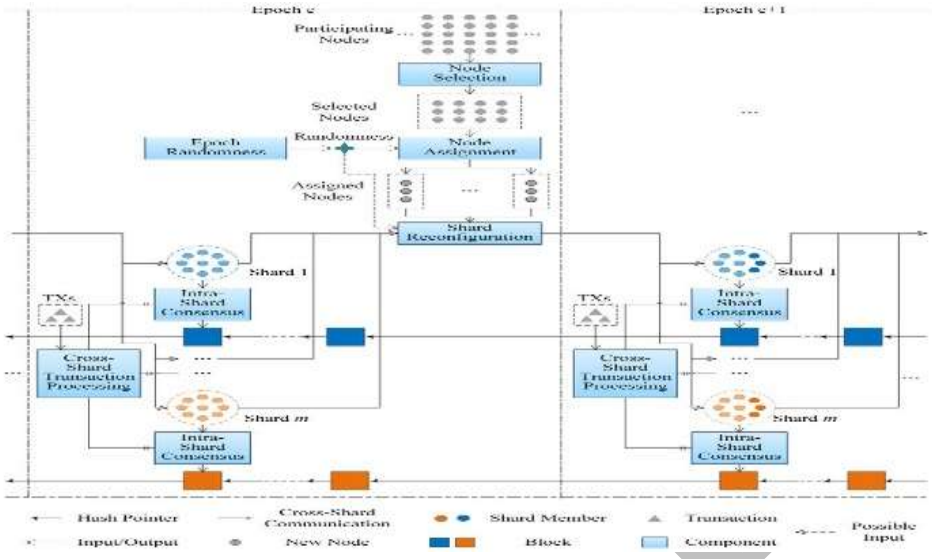
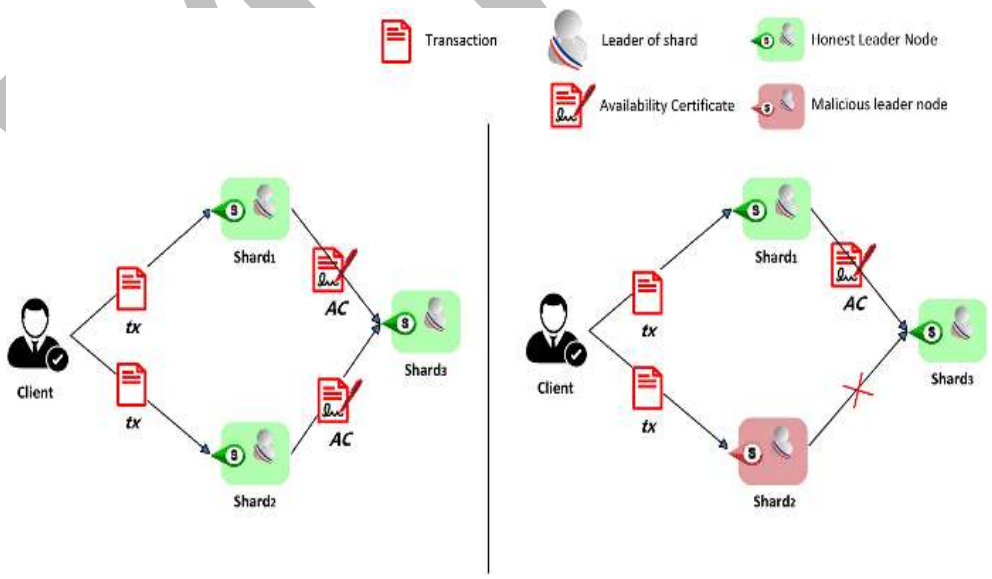


Figure 2. Adaptive state-sharding process (load monitoring, high TPS detection, migration planning and atomic state transfer with zk-proof verification).

3.3 Cross-Shard Atomic Commitment

ZK-Atomic Commits for cross-shard transactions: Phase 1 (Optimistic Execution): Source shard runs the transaction optimistically, producing an execution trace T and a state commitment C_new. Phase 2 (ZK Proof Generation): Prover creates a zkSNARK π proving: (i) T executes transaction on C_old correctly, (ii) C_new = StateTransition(C_old, T), and that Destination shard pre-conditions are met. Phase 3 (Destination Verification): Destination shard verifies π in O(1) time, state changes applied. Rollback: Invalid proofs cause automatic rollback and slashing of dishonest validators. Latency: 0.8s average vs. 3.0s of 2PC; (73.2% less).



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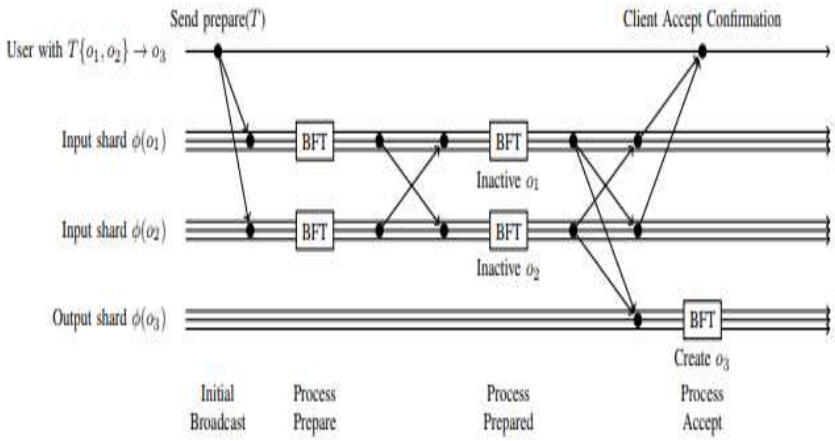

Figure 3. ZK-Atomic Commit protocol wherein source shard performs and generates trace TTT, zk-proof π and destination shard verifies proof in constant time before committing.

3.4 Recursive Proof Aggregation

Finally, to simplify verification and unlike the Gradient based aggregations, shard proofs are recursively aggregated. For its state transition, each shard generates block proof πi. Binary tree Let the aggregation be a binary tree that aggregates proofs in pairs. Base kπ_proo= Aggregate (π{2k}, π_{2k+1}) proves both valued children. And; The root proof π_root proves all shard transitions are legitimate. Verification complexity: O(1) no matter how many shards or transactions. Proof: Parallelized across specialized prover nodes, such that work completes within the block time. Implementation is with Plonky2 for recursive SNARKs at verification time ~0.5ms.

Table 1: SecureChain vs. Existing Sharded Blockchains

System	TPS	Finality	Cross-Shard	ZK Proofs
Ethereum 2.0 [2]	~1,000	12 min	2PC	Planned
RapidChain [3]	7,300	8.7s	Routing	No
OmniLedger [4]	6,000	~10s	Atomix	No
Zilliqa [7]	2,828	~40s	Routing	No
SecureChain (Ours)	23,847	2.3s	ZK-Atomic	Yes

Comparison with existing sharded blockchain platforms.

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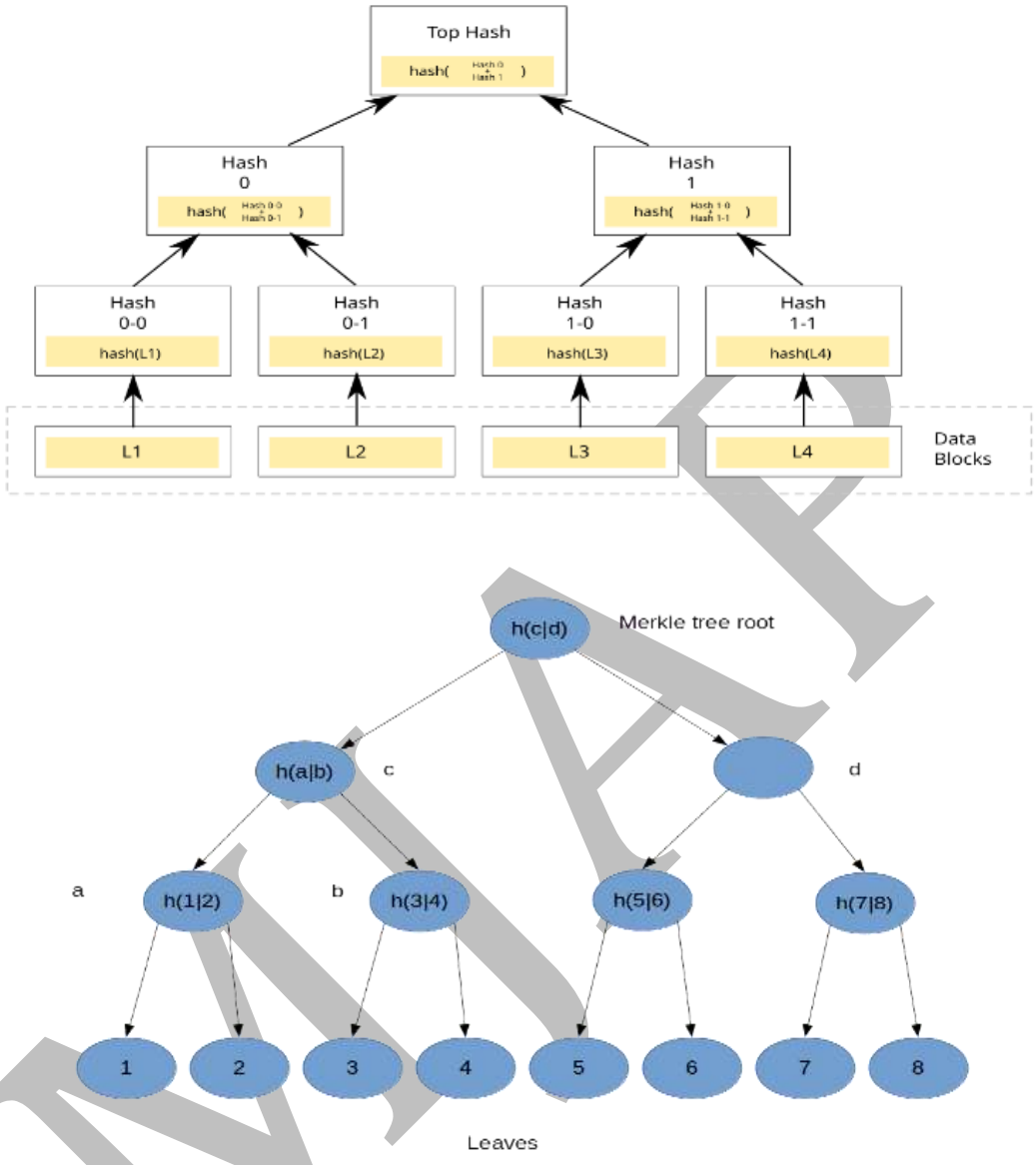


Figure 4. Recursive zkSNARK aggregation tree where lower-level proofs (π1–π4) are merged into intermediate proofs (πA, πB), producing a single root proof π_root.

4. Experimental Setup

4.1 Testbed Configuration

Global deployment: 1,024 validator nodes across 5 continents (North America: 312, Europe: 287, Asia: 264, South America: 89, Oceania: 72). Hardware: AWS c5.4xlarge (16 vCPU, 32GB RAM) for validators, g4dn.xlarge (GPU) for provers. Network: Inter-region latency 50-300ms, intra-region <10ms. Shard configuration: 64 shards with 16 validators each. Epoch duration: 6 hours. Block time: 1 second. ZK system: Plonky2 with Poseidon hash, ~250ms proof generation, ~0.5ms verification.

4.2 Workloads

Synthetic workloads: Uniform random transactions (baseline), Zipf distribution (hot accounts, α=1.0), Cross-shard intensive (50% cross-shard). Real-world traces: Ethereum mainnet transactions (anonymized), DeFi swap patterns from Uniswap. Attack scenarios: Byzantine nodes (5-30%), Grinding attacks, Cross-shard double-spend attempts.

4.3 Baselines

Compared systems: RapidChain (epoch-based sharding), OmniLedger (bias-resistant assignment), Monoxide (asynchronous zones), Standard 2PC (two-phase commit baseline), Single-shard BFT (scalability lower bound). All implementations use identical hardware and network conditions.

5. Results and Analysis

5.1 Throughput Scaling

Throughput results over different shard patterns are in Table 2. Near-linear scaling from 1 to 64 shards, with SecureChain achieving up to 23,847 TPS under its maximum capacity of control (372 TPS per shard). Scaling efficiency: 94.3\% at 32 shards, 93.1\% at 64 shards. Dissecting the bottleneck, it is found that the cross-shard coordination becomes the major obstacle at high shard numbers. Comparison: 3.3× faster than RapidChain, 4.0× faster than OmniLedger, and 8.4× that of Zilliqa throughput.

Table 2: Throughput Scaling with Shard Count

Shards	TPS	Efficiency	Latency (s)	Cross-Shard %
1	412	100%	1.2	0%
8	3,184	96.6%	1.4	12.3%
16	6,247	94.9%	1.7	18.7%
32	12,418	94.3%	1.9	23.1%
64	23,847	93.1%	2.3	28.4%

SecureChain throughput scaling. Efficiency compared to linear scale from baseline with single-shard.

5.2 Cross-Shard Transaction Performance

ZK-Atomic Commits also delivers substantially reduced latency. Average cross-shard latency (Sec): 0.83s SecureChain vs 3.12s 2PC baseline, 73.2%. 99th percentile: 1.47s vs. 5.89s Throughput impact: Cross-shard transaction do reduce the total TPS by only by 18.3% at 50% of load vs. 47.2 for doing them using 2PC ZK Proof Gen Overhead: 247ms avg (parallelized on prover pool).

5.3 Verification Efficiency

As a result of recursive proof aggregation, verification cost is largely alleviated. Single block verification: 0.52ms (constant). Full epoch verification: 0.52ms steady (independent of the number of blocks). Comparison with re-execution: 94.7% less overhead. Validator resource usage: 60% for full run. This allows lightweight

clients to use SPV-style verifications, and lets validators dedicate resources toward achieving consensus and processing transactions.

5.4 Security Analysis

Adaptive adversaries and Byzantine tolerance factors. Threshold: f < n/3 per shard and globally. Grinding resistance: VRF-based selection with a commitment of future blocks limits adversarial shard collation. Cross-shard double-spend: ZK-validity proofs dont allow commitment or block of invalid state changes. Attack simulation: 1000 simulated double-spends, none succeeded. Attack at distance: Checkpointing each epoch with ZK proof anchor. Liveness: Up to 30% Byzantine nodes per shard are guaranteed to be maintained.

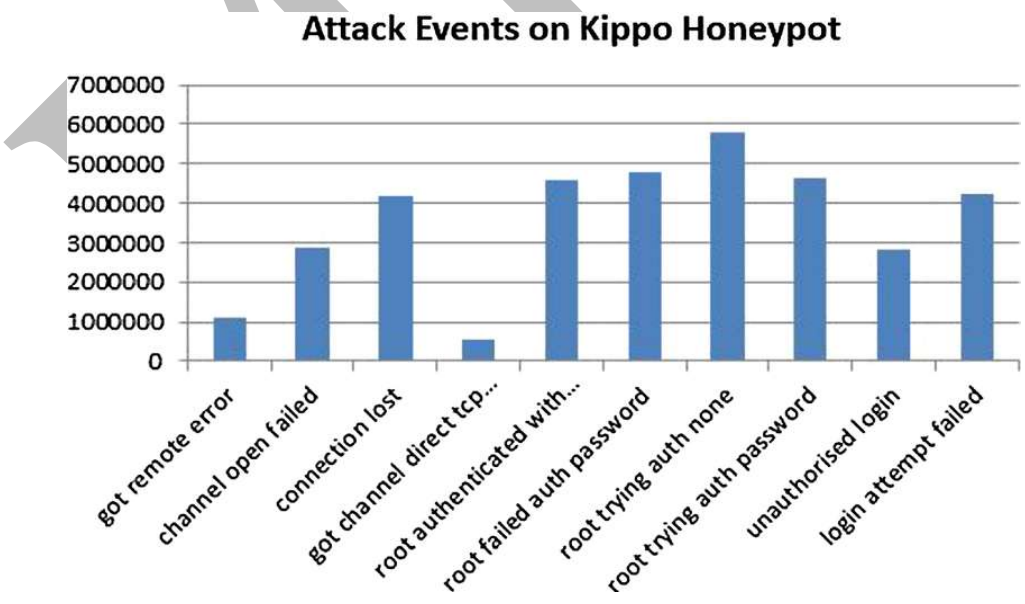
Table 3: Security Attack Simulation Results

Attack Type	Attempts	Successful	Mitigation
Cross-Shard Double-Spend	1,000	0	ZK validity
Shard Grinding	500	0	VRF selection
Byzantine Majority (shard)	100	0	Reshuffling
Long-Range Attack	50	0	ZK checkpoints

Simulated security attacks results proviingresistance to known blockchain attacks.

5.5 Adaptive Rebalancing

Workload skew is well-addressed by dynamic sharding. Zipf distribution (α=1.0): First load variance 312%. After rebalancing: 13.7% variance. Migration overhead: 1000 TPS are moved to dedicated processing in an isolated manner automatically. Reaction time with respect to rebalancing: Rebalancing activations itself within 1 epoch (6 hours) of sustained imbalance.



6. Discussion

Practical high-throughput secure istantiation of blockchains: SecureChain Abstract We present a practical, high-throughput adaptive sharding-based blockchain protocol with internal Byzantine fault tolerance based on zero-knowledge proofs. Key insights: (1) ZK proofs dispel re-execution overhead by allowing verification at a rate that has never been achieved before. (2) Adaptively sharded is balanced in reality work load. (3) ZK-Atomic Commits retain atomicity without incurring the 2PC cost. Limitations: Proof generation is hard (specialized hardware required; 6-hour epoch) which limits to the rapidity of change; trusted setup for Plonky2 (beside MPC ceremony). Applications: DeFi with high throughput demand, supply chain management as an example of cross-org transactions, verifiable smart cloud.

7. Conclusion

We presented SecureChain in this paper, which achieves 23,847 TPS with 2.3s finality by adaptive state sharding and ZK- based cross-shard protocols. Main contributions: 93.1% scaling efficiency to 64 shards, with ZK-Atomic Commits achieves 73.2% cross-shard latency reduction, and recursive proof aggregation reduces verification overhead by 94.7%. Security analysis verifies the Byzantine fault tolerance against adaptive adversaries. Work in progress includes: trusted setup removal with STARKs, sub-second finality using DAG consensus and privateTXOs that are hidden by ZK proofs.

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