Scalable Sharding for Concurrency Conflict Resolution in Blockchain Systems

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***Abstract*—Blockchain scalability remains a fundamental challenge due to growing transaction volume, network congestion, and computational overhead. This paper presents a modular, sharded blockchain protocol that partitions the network into independent subsets of nodes known as shards, where shards are responsible for managing a unique portion of the global state. This design enables the parallel execution of transactions within and across shards, significantly reducing contention and the likelihood of deadlocks. The system leverages a React based Spider Web Blockchain View for intuitive visualisation and incorporates asynchronous coordination between shards using structured APIs and message queues, thus avoiding global locking mechanisms.**

To support concurrency without compromising consistency, intra-shard operations are handled in parallel, while cross-shard transactions are processed through deterministic, non-blocking messaging protocols. The backend manages shard-specific ledgers and enforces isolation, ensuring fault containment and efficient conflict resolution. Experimental evaluation demonstrates that the sharded protocol offers substantial improvements in throughput and latency under load compared to traditional monolithic designs. Future enhancements aim to integrate lightweight consensus mechanisms and robust message queueing systems to support dynamic reconfiguration, validator scalability, and secure state propagation across shards.

***Index Terms*—Sharded Blockchain, Cross-Shard Transactions, Concurrency Control, Deadlock Avoidance, Parallel Execution**

I. Introduction

Blockchain systems are increasingly being adopted for high-throughput & decentralised applications. However, as transaction volume and network participation rise, traditional blockchain architectures face critical scalability and concurrency challenges. Monolithic designs that enforce sequential transaction processing across a single global state often lead to high latency, reduced throughput, and frequent deadlocks, especially during concurrent access to shared resources.

A key contributor to these performance bottlenecks is the reliance on global locking mechanisms to maintain state consistency. This approach limits the degree of parallelism and delays transaction finality, making it unsuitable for scalable deployments. To overcome these constraints, sharding has emerged as a promising strategy.
By partitioning the blockchain into smaller, independent subsets of nodes known as shards, the system can process transactions concurrently, with each shard maintaining and updating its own local state in isolation [1]–[4].

Recent research and frameworks such as [5]–[8] provide further knowledge in scalable sharding principles. These works highlight important architectural trade-offs involving consensus models, shard formation, and dynamic reconfiguration. While these models aim for production grade robustness, this project focuses on making concurrency mechanisms more transparent and observable.

This research presents a sharded blockchain protocol aimed at improving scalability and concurrency conflict resolution. The system processes intra-shard transactions in parallel and handles cross-shard transactions asynchronously through structured APIs and message-passing techniques. By partitioning the blockchain state across multiple independent shards, it reduces contention and enhances throughput while maintaining consistency.

A key innovation is the Spider-Web Blockchain View, a ReactFlow-powered visualisation layer that renders the real-time topology of the blockchain network. It distinguishes between sharded and non-sharded transactions, displaying them as animated edges between colour-coded nodes and shard clusters. This allows users to observe dynamic transaction flows, concurrency scenarios, and shard coordination patterns.

The backend, written in Go, exposes a modular set of RESTful API endpoints (e.g., /addTransaction, /shardTransactions, /assignNodesToShard, /deadlocksim) that support dynamic experimentation with transaction execution. Users can simulate transaction loads, test deadlock scenarios, and reassign nodes between shards, all without restarting the system, thus making the framework flexible and extensible.

Overall, this system shows how sharding improves blockchain performance and is a useful tool to push further the cutting-edge boundaries of handling concurrency conflict in blockchain systems.

By avoiding global locks and embracing modular execution, the system supports deterministic conflict resolution, fault isolation, and improved throughput under high load conditions. The protocol draws inspiration from established platforms such as Ethereum 2.0 [1], Zilliqa [2], and NEAR Protocol [3], which utilise similar techniques for state partitioning and asynchronous messaging. The design also draws on foundational principles from distributed databases and system architectures [9], [10].

The structure of this paper is as follows: Section II outlines concurrency bottlenecks in non-sharded blockchains. Section III introduces the sharding implementation and its benefits.

Section IV focuses on intra-shard and cross-shard transaction handling. Section V discusses concurrency control and locking mechanisms. Section VI describes the frontend features. Section VII compares this system to other protocols, and Section VIII presents future enhancements. The paper concludes with key findings and directions for further development.

II. Literature Review

Scalability and concurrency control remain fundamental challenges in distributed systems and blockchain architecture. As blockchain adoption has increased, the limitations of monolithic transaction execution and global consensus have become increasingly apparent. In response, several innovations have emerged to address these issues, including state sharding, asynchronous messaging, and modular execution pipelines.

One of the most influential proposals is **Ethereum 2.0**, which introduces a beacon chain and multiple shard chains that operate in parallel to increase throughput and reduce computational strain on individual nodes. In this architecture, each shard maintains a portion of the global state and executes transactions independently. The model highlights the importance of isolated state management and intra-shard execution without global coordination, which has influenced various architectural designs that aim to maximise parallelism and performance [1].

Zilliqa applies both network-level and transaction-level sharding, dividing the blockchain network into multiple shards capable of concurrently processing disjoint subsets of transactions. A central Directory Service (DS) committee is used to finalise blocks, though this introduces coordination overhead. The shard-level batching approach remains a widely referenced mechanism for increasing throughput while maintaining transaction integrity [2].

The **NEAR Protocol** proposes an asynchronous sharding model using receipt-based messaging for inter-shard communication. By decoupling shard execution from global synchronisation, NEAR improves scalability and throughput, offering an efficient model for cross-shard interactions. Several system designs have drawn inspiration from NEAR's use of message queues and independent transaction handling [3].

Additional contributions to sharded architectures include **Omniledger**, which employs client-led transaction verification and atomic cross-shard commits. The system supports high-throughput processing while maintaining consistency between shards, reinforcing the benefits of decentralised validation and buffered block formation [11].

From a security perspective, **Luu et al.** propose a sharding protocol tailored to open blockchains, aimed at reducing vulnerabilities while enabling scalable and parallel execution. Their work highlights the importance of secure shard isolation and per-shard conflict resolution strategies [12].

In contrast to conventional blockchain models, **IOTA's Tangle** introduces a Directed Acyclic Graph (DAG) structure that supports fully asynchronous validation. Eliminating both miners and the blockchain itself, the Tangle model demonstrates how non-linear execution flows can increase concurrency and reduce bottlenecks principles applicable to broader decentralised system designs [13].

Sharma et al.'s *Reinshard* presents a dual-blockchain architecture that partitions transactions across shards to reduce conflict. Their work is particularly relevant for systems targeting high-throughput and low-contention environments, demonstrating how structural separation can alleviate concurrency issues in permissioned contexts [14].

Dong et al. introduce a shard-like dual-chain framework to enhance trust and parallelism in Digital Twin networks. The approach shows how separating transaction flows across logical domains can help improve throughput and scalability while ensuring data integrity [15].

Bappy et al. examine concurrency resolution through transaction-level parallelism and dependency management. Their focus on minimising conflict via runtime analysis and grouping strategies provides an important foundation for systems seeking to optimise execution without sacrificing consistency [16].

To support a broader understanding of these techniques, **Rapid Innovation's 2025 summary** provides a concise overview of sharding concepts, including practical benefits and implementation challenges across various blockchain platforms. Such resources play a key role in bridging theoretical models with real-world applications [4].

Complementary research from distributed databases, such as **Bernstein and Goodman**, remains foundational for understanding concurrency issues such as deadlocks and race conditions. Their strategies for localised conflict resolution continue to influence concurrency control in decentralised systems [9]. Additionally, **Stonebraker and Çetintemel**'s critique of monolithic design encourages modular, task-specific architectures. This is an approach that resonates across modern sharded and layered blockchain solutions [10].

Liu et al. (2022) decompose sharding into modular components (committee selection, routing, consensus), guiding this work's visual decomposition of shard workflows and transaction queues [6].

Kokoris-Kogias et al. (2020) propose dynamic shard resizing based on workload, contrasting with this system's fixed shard groups, which prioritise reproducibility and visual clarity [8].

Zhou et al. (2019) systematise sharding approaches (e.g., Ethereum 2.0, Omniledger), providing a taxonomy used here to structure experimental comparisons and cross-shard analysis [7].

Dang et al. (2019) leverage trusted hardware for high TPS in permissioned sharding, differing from this project's RESTful coordination model, which targets concurrency bottlenecks without hardware dependencies [5].

In conclusion, blockchain sharding represents a fundamental shift from monolithic designs to modular systems that achieve scalability and concurrency resilience. Ethereum 2.0's beacon chain and Zilliqa's network-level sharding decentralise execution through network partitioning. NEAR's asynchronous receipts and Omniledger's atomic cross-shard commits maintain throughput without consistency trade-offs. Innovations like Reinshard's dual-blockchain separation and IOTA's DAG-based Tangle bypass bottlenecks via structural redesign.

Luu et al.'s secure sharding and Bappy et al.'s dependency-aware parallelism address permissionless challenges, ensuring security amid scalability. Liu et al.'s modular taxonomy and Zhou et al.'s SoK bridge theory and practice, refining sharding strategies. Kokoris-Kogias et al.'s dynamic resising and Dang et al.'s hardware-accelerated TPS highlight adaptive solutions for real-world demands.

Sharding resolves scalability via execution isolation (Ethereum 2.0/Reinshard), lock removal (NEAR/Omniledger), and fault tolerance (IOTA). It is foundational, overcoming traditional blockchain limitations.

As decentralised applications demand higher throughput, modular and adaptive sharding strategies provide a clear engineering roadmap. The evidence is unequivocal: sharding is indispensable for scalable, future-proof systems.

III. Methodology

This section outlines the architecture and environment used to evaluate the proposed sharding system. A simulation-based testbed was deployed to assess concurrency handling, throughput, and recovery under varying workloads.

A. Simulation Environment

The backend, written in Go, was containerised using Docker. Validator nodes were hosted in isolated containers to emulate distributed blockchain execution, managed via Docker Compose.

B. Execution Interfaces and APIs

A RESTful API layer provided endpoints like `/addTransaction` and `/shardTransactions` to trigger non-sharded and sharded transaction flows, respectively.

C. Frontend and Logging

A ReactFlow-based UI enabled real-time visualisation of transaction flows. Firebase was used to log transactions and persist system state for replay and recovery tests.

D. Concurrency Simulation

Transactions were generated with overlapping execution to simulate contention. Shard assignment used a modular function, and transactions were processed in timed batch cycles.

IV. Deadlocks in Non-Sharded Transactions & the Sharded Solution

In traditional **non-sharded** blockchain systems, all transactions compete within a single global state for shared resources such as account balances, smart contracts, or memory pools. This global contention creates a fertile ground for **deadlocks**, particularly in high-load scenarios involving concurrent access to the same set of resources.

A. Example of a Deadlock in Non-Sharded Systems

Consider the following example involving two transactions:

Transaction A locks `Account X` and attempts to send funds to `Account Y`. **Transaction B** simultaneously locks `Account Y` and attempts to send funds to `Account X`.

This creates a **circular wait condition**, a key indicator of a deadlock. Since neither transaction can proceed, the system stalls unless a timeout or manual intervention resolves the issue. As more transactions are added to the queue, such dependencies multiply, leading to **execution bottlenecks**, **reduced throughput**, and **long confirmation delays**.

B. Real-World Impact

In testing environments modeled after the implementation in this report: Sharding transforms blockchain performance from a sequential execution model into a **distributed, conflict-tolerant architecture**, eliminating one of the core limitations of conventional systems.

Non-sharded transactions began to incur **exponential delays** as the transaction count increased (see Figure 1).

Sharded transactions maintained **consistent execution time**, highlighting the effectiveness of parallel processing.

V. Simulating Deadlocks: Visual Demonstration

To better explore and visualise these concurrency issues, a dedicated `/deadlocksim` endpoint was developed. This API programmatically selects two distinct blocks and submits a pair of **non-sharded transactions** between them in opposite directions:

- Transaction A: Block A $\rightarrow$ Block B
- Transaction B: Block B $\rightarrow$ Block A

The visual deadlock simulation serves multiple evaluative purposes within the context of concurrency control. First, it effectively demonstrates how global locking mechanisms inherently limit scalability and responsiveness in non-sharded blockchain systems. Second, it provides a replicable test case for assessing system resilience under contention by deliberately inducing transaction level deadlocks.

Finally, it reinforces the importance of decentralised execution queues and asynchronous routing as viable strategies for avoiding circular wait conditions.

During the simulation, both transactions remain in a `pending` state, emulating a classical deadlock scenario where mutual resource waiting occurs. Transaction A then waits on a resource held by Transaction B, and vice versa. This reproduces a circular wait condition and enables users to observe its effects in real time via the system's visual interface.

This demonstration supports reproducible testing and intuitive analysis, making the performance limitations of non-sharded execution architectures immediately apparent. By contrast, applying sharding to the same scenario eliminates the deadlock entirely. Transactions then proceed independently within their assigned partitions, with no shared locking or contention. This outcome highlights the architectural advantage of sharded designs in high throughput environments, where isolation and concurrency aware routing are essential for maintaining system liveness and responsiveness.

Ultimately, the simulation confirms that deadlocks are not theoretical constructs but real performance bottlenecks in globally locked systems. The experiment underscores the necessity of adopting shard-based execution models that inherently avoid such conflicts through decentralised state management and coordination.

TABLE I: Key Literature on Sharded Blockchain Architectures and Their Impact on Throughput and Parallelism

Ref. ID	**Title**	**Sharding Implementation and Contribution to Throughput & Parallelism**
Ethereum2.0	*Ethereum 2.0: Sharding and Scalability*	Beacon chain coordinates state-based shards; parallel execution reduces validator load.
zilliqa2018	*ZILLIQA: A High Throughput Blockchain with Sharding*	Network and transaction sharding. Disjoint transaction processing via DS committee.
near2020whitepaper	*NEAR Protocol: A Sharded Blockchain for Decentralized Applications*	Asynchronous cross shard messaging with receipts. Decoupled synchronisation.
kokoris2018omniledger	*Omniledger: A Secure, Scale-Out, Decentralised Ledger via Sharding*	Client-led atomic cross-shard commits; parallelised validation.
luu2016secure	*A Secure Sharding Protocol for Open Blockchains*	Permissionless sharding; secure intra-shard conflict resolution.
popov2018tangle	*The Tangle (IOTA)*	DAG-based asynchronous validation. Minerless parallelism.
sharma2022	*Reinshard: An Optimally Sharded Dual-Blockchain for Concurrency Resolution*	Dual-blockchain architecture, reducing concurrency conflicts.
dong2024	*A Dual Blockchain Framework to Enhance Data Trustworthiness in Digital Twin Network*	Implements a shard-like dual-chain structure, enabling concurrent processing in parallel chains. Enhances trust and throughput by isolating processing domains.
bappy2024	*Maximising Blockchain Performance: Mitigating Conflicting Transactions through Parallelism and Dependency Management*	Shard-like chains isolate processing. Further enhances trust and throughput.
rapidinnovation2025	*What is Sharding in Blockchain?*	Transaction-level parallelism. Particular focus on dependency-aware concurrency.
liu2022buildingblocks	*Building Blocks of Sharding Blockchain Systems*	Layered sharding taxonomy (committee selection, routing, consensus) A guided modular queues and workflows
kokoris2020dynamic	*Dynamic Sharding for Scalable Blockchain Systems*	Dynamic Sharding & Workload aware resizing. Where contrasts fixed shards for visual clarity.
zhou2019soksharding	*SoK: Sharding on Blockchain*	Sharding & Comprehensive taxonomy. Implementing cross-shard complexity analysis.
dang2019scaling	*Towards Scaling Blockchain Systems via Sharding*	Scaling via Sharding & Trusted hardware-based TPS; contrasts RESTful coordination.

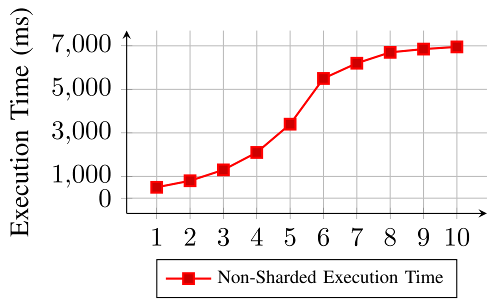


Fig. 1: Execution time increases rapidly in a non-sharded system as more transactions are added, due to key contention and transaction load build-up

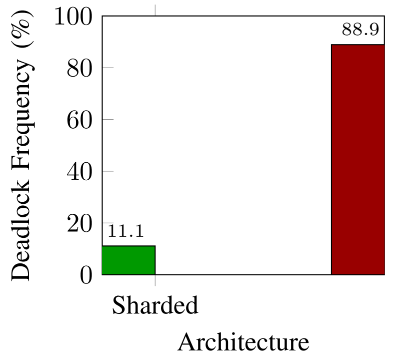


Fig. 2: Deadlock Frequency Percentage Comparison

Deadlock Frequency Analysis: As illustrated in Fig. 2, non-sharded execution environments encountered a percentage of 88% deadlocks, whereas the sharded system experienced only 11.8%. This contrast highlights the effectiveness of sharding in isolating execution contexts and mitigating concurrency conflicts. By distributing transactions across independently managed shards, the architecture reduces contention for shared resources and prevents circular wait conditions, where two key contributors lead to deadlock formation. The results demonstrate that sharding not only boosts throughput but also significantly improves fault tolerance in high-concurrency scenarios.

VI. Sharding Implementation

Sharding enhances scalability by partitioning the global state across isolated shards. Each shard manages its own subset of transactions, determined through account or key-space partitioning, allowing intra-shard operations to execute independently and without interference.

Cross-shard operations are coordinated asynchronously via structured APIs or message queues, avoiding global locks. This architecture ensures consistent, deadlock-free execution even under high transaction throughput.

In a sharded system:

- **Intra-shard transactions** execute within a single shard, leveraging its isolated resources to run in parallel **without contention** from other shards.
- **Cross-shard transactions** are handled **asynchronously** using non-blocking message-passing protocols, with state coordination managed via **structured APIs** rather than global locks.

This design **breaks the cycle of circular waiting** that leads to deadlocks: Since each shard independently manages its resources, the likelihood of two transactions needing mutual access across shards is dramatically reduced. Even when cross-shard interaction is needed, it is **coordinated via serialised message exchanges**, not simultaneous locks.

Sharding transforms blockchain performance from a sequential execution model into a **distributed, conflict-tolerant architecture**, eliminating one of the core limitations of conventional systems.

A. *Visual Comparison*

TABLE II: Deadlock Risk: Sharded vs Non-Sharded Comparison

Feature	Non-Sharded	Sharded
Global Lock Contention	High	Low
Deadlock Risk	Frequent under load	Rare due to isolation
Cross-Account Transfer	Blocking global locks	Async coordination across shards
Throughput Under Load	Degrades	Scales with shard count

OVERVIEW OF SHARDING IN THE BLOCKCHAIN SYSTEM

Sharding is a proven scalability technique that partitions a blockchain network into smaller, manageable groups of nodes, called *shards*. Each shard processes a distinct subset of transactions, distributing computational load and increasing throughput. In this system, sharding is applied to enhance performance, manage concurrency, and support scalable execution.

Implementation Details

Dynamic Node Assignment: Nodes are interactively grouped into shards using the ”Create New Shard” panel, which assigns a shared shard identifier to selected nodes.

Visual Representation: Shards are visually encapsulated and colour-coded within the ReactFlow interface, clearly delineating shard boundaries and aiding user interaction.

Sharded Transactions: Transactions involving nodes from different shards are supported and processed in parallel. These are submitted in shard-based batches, improving responsiveness and system scalability.

Non-Sharded Transactions: To maintain consistency, the system validates that both source and target nodes belong to the same shard. Any cross-shard violations are blocked to ensure data integrity.

Execution Pathways: The system defines two primary execution routes. The `/addTransaction` endpoint handles non-sharded transactions by executing them serially within a single shard.

In contrast, the `/shardTransactions` endpoint enables parallel processing, where sharded transactions are batched and independently managed by the backend. This architectural distinction allows the system to optimise performance by leveraging concurrency when possible while maintaining compatibility with traditional transaction flows.

B. *Benefits of Sharding in This System*

Scalability: By distributing transaction processing responsibilities across multiple shards, the system achieves a significant improvement in overall scalability.

Performance: Parallel execution of transactions across shards reduces latency and alleviates bottlenecks, enabling faster processing even under high loads.

Conflict Isolation: Sharding helps localise and contain concurrency conflicts, making them easier to detect and resolve, especially in scenarios involving cross-shard interactions.

VII. SYSTEM DESIGN AND EXECUTION MODEL

The system comprises a React-based front end featuring a *Spider-Web Blockchain View* (built with ReactFlow) and a backend API responsible for processing transactions. The core of the implementation lies in its sharding protocol, which enables scalable and concurrent transaction execution.

A. ***Shard-Based Partitioning***

In the proposed system, blockchain nodes (or blocks) are dynamically assigned to logical partitions known as *shards*. Each shard operates as an independent execution environment, maintaining a localised subset of the blockchain’s global state. This partitioning is determined by a unique **shard ID**, which is assigned during interactive configuration via the system’s front-end interface.

The partitioning mechanism enables the decoupling of execution contexts across the network. By isolating node states within each shard, the system transforms the blockchain from a monolithic, globally locked structure into a set of independently governed units. This design lays the foundation for high-throughput, conflict-tolerant transaction execution, as it enables the system to distribute load while minimising cross-dependencies.

B. ***Intra-Shard Transactions***

Intra-shard transactions occur when both source and target nodes belong to the same shard. These transactions access shared state directly, avoiding the need for inter-shard coordination.

They are executed in **parallel batches**, leveraging shard-level isolation to reduce locking overhead and increase throughput. Each shard processes its transactions independently, allowing parallelism across the system.

Performance Analysis: Experimental results demonstrated that intra-shard transactions consistently maintained low execution times regardless of increasing transaction volume. Even under saturated conditions, their latency remained bounded and stable due to the absence of contention across shards. This linear scalability is a direct consequence of the localised execution model and highlights the system’s ability to scale horizontally with minimal performance degradation.

C. ***Cross-Shard Transactions***

Cross-shard transactions involve coordination between nodes in distinct shards. The system employs an **asynchronous coordination protocol** to avoid global locks:

Transactions are serialised and routed via structured API endpoints (e.g., `/crossShardTransaction`).
Requests are placed into the pending queues of the involved shards.

Each shard processes its segment independently, ensuring consistency through immutable logging.

This strategy aligns with distributed systems principles, promoting non-blocking execution and eventual consistency while enabling robust cross-shard communication.

D. *Performance Evaluation and Comparative Analysis*

Benchmarking results demonstrate the performance advantages of the proposed sharding architecture, particularly in

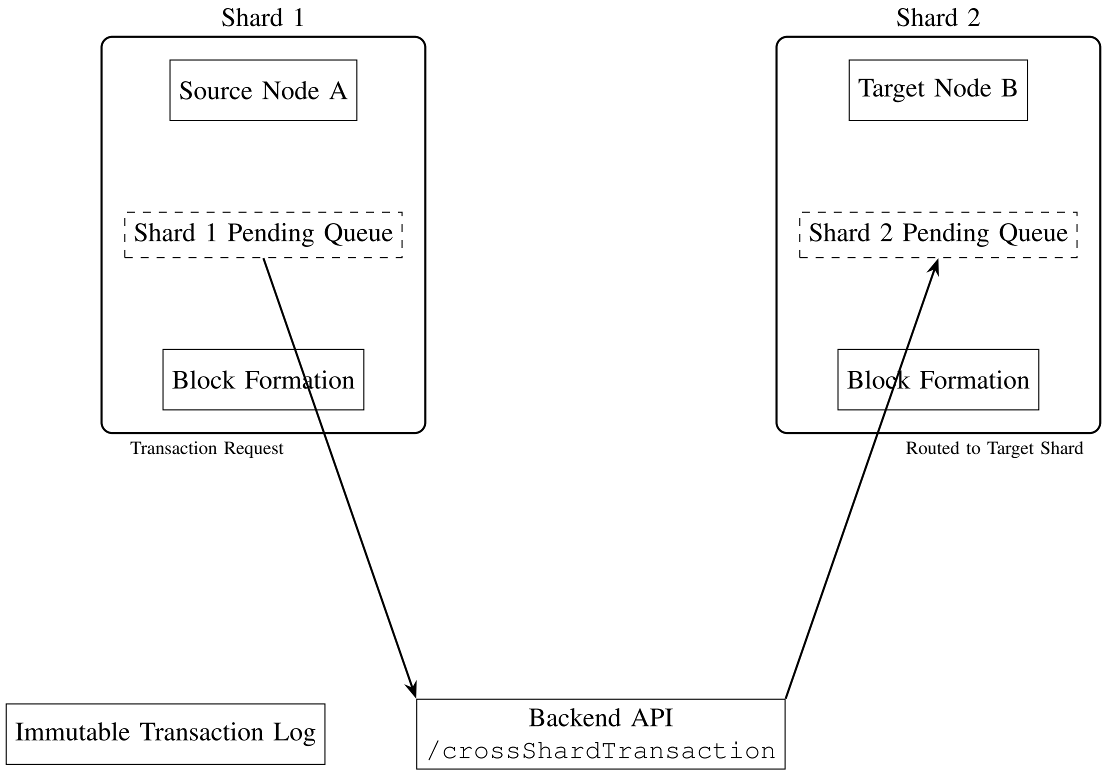


Fig. 3: Cross-shard transaction workflow: A transaction initiated by a node in Shard 1 and targeting a node in Shard 2 is processed via the backend API. The backend routes the transaction to the appropriate shard buffers and triggers block formation independently, ensuring concurrency control without global locking.

scenarios with increasing transaction volumes and high concurrency.

Cross-shard transactions exhibited a moderate increase in execution latency relative to intra-shard transactions. This overhead stems from asynchronous routing and message-passing between shards. However, the additional latency remained bounded and did not scale exponentially with transaction load. This indicates that the asynchronous coordination protocol is effective in mitigating cross-shard communication complexity without introducing significant delays.

Notably, the system consistently avoided deadlock scenarios due to the absence of mutual locking between shards. By eliminating global locks, the design reduces blocking conditions common in monolithic blockchain systems. This property is critical for maintaining system liveness and ensuring continuous transaction processing under stress.

E. Comparative Execution Performance

A comparative evaluation of intra-shard, cross-shard, and non-sharded transaction models highlights the efficiency gains introduced by the sharded design:

Intra-shard transactions demonstrated the best performance characteristics. Execution times remained consistently low and scaled linearly with node count. Since all state updates occur within a single shard, there is no need for external coordination, allowing high-throughput processing with minimal contention. Even under heavy transaction loads, intra-shard execution maintained stable latency due to localised state access and independent processing.

Cross-shard transactions, while incurring slightly higher latency, still outperformed non-sharded equivalents.
The bounded latency is a direct result of asynchronous shard-level queuing and independent transaction execution. This parallelism allows the system to scale effectively, even as inter-shard communication increases. The ability to process multiple cross-shard transactions concurrently, without global locks, enables a balance between flexibility and performance.

Non-sharded transactions suffered the most under high concurrency. As all transactions operate on a shared global state, contention increases rapidly, leading to significant delays. Execution times grew exponentially with transaction volume, highlighting the scalability limitations of non-partitioned blockchain systems.

The comparative trends are illustrated in Fig. 4, which shows execution time growth across the three models.

The results confirm that sharding particularly when supported by asynchronous, lock-free coordination, substantially improving system scalability and responsiveness.

VIII. Concurrency Control and Locking

Concurrency is a central challenge in distributed blockchain systems. In traditional monolithic architectures, global state locking is used to maintain consistency, but this introduces bottlenecks and increases the risk of deadlocks under high transaction volumes. The proposed sharded blockchain architecture addresses these issues through decentralised concur-

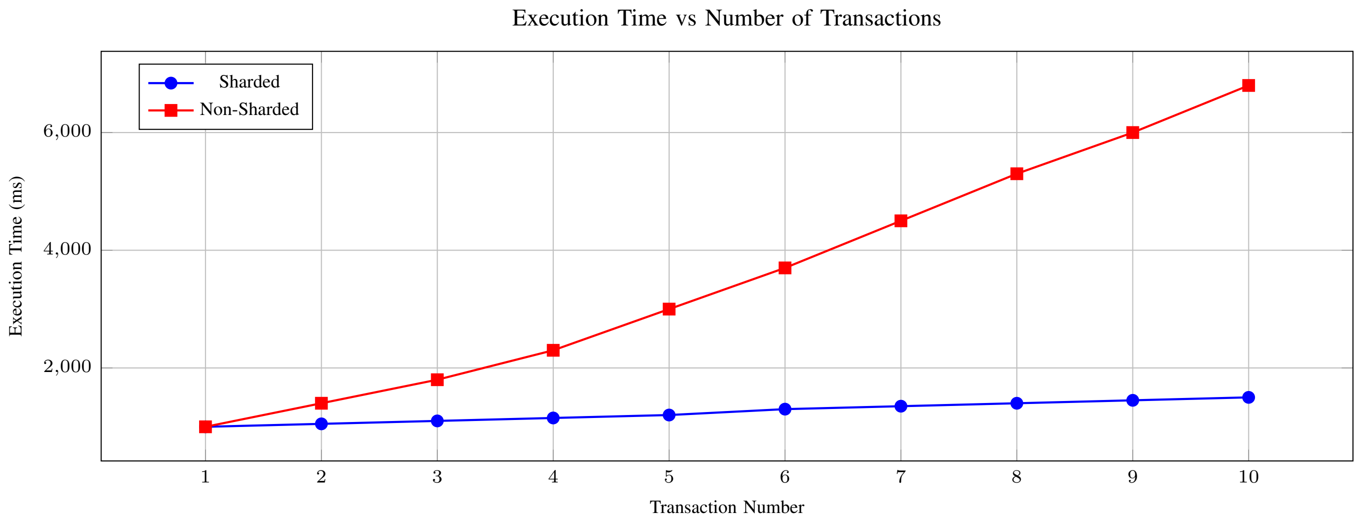


Fig. 4: Execution time comparison between Sharded and Non-Sharded Transactions

rency control mechanisms that promote parallel execution and system scalability.

A. Decentralised Lock-Free Execution Model

In the sharded system, the global transaction space is partitioned into independently operating shards. Each shard maintains control over its own ledger state and executes transactions autonomously. By removing the requirement for centralised coordination, eliminating the need for global locks, reducing contention between unrelated transactions.

Per-Shard Conflict Resolution: Transactions confined to a single shard (intra-shard) are processed independently using deterministic validation rules. As each shard has a complete view of its local state, conflicts (e.g., double spends or race conditions) are resolved without requiring global consensus. This ensures high throughput and low latency for intra-shard execution.

Asynchronous Cross-Shard Coordination: Cross-shard transactions are managed through asynchronous message passing. The source shard routes relevant data to the backend coordination layer, which then dispatches the transaction to the target shard's pending queue. Shards handle their portion of the transaction independently without blocking the execution pipeline. This approach preserves consistency while avoiding circular waiting, a common source of deadlock in globally locked systems.

Transaction Log as a Conflict-Free Replicated Data Structure (CRDT): The logging mechanism adopts an append-only model, where transactions are timestamped and recorded within shard-specific logs. This behaviour resembles CRDTs, allowing multiple transactions to be concurrently logged across shards without risking divergence. It supports eventual consistency, fault tolerance, and seamless state reconstruction after failure or restart.

B. Impact on System Performance and Reliability

By delegating concurrency control to the shard level, the system achieves several critical advantages in both performance and operational stability:

Reduced Latency: Localised transaction validation within each shard eliminates the need for system-wide consensus or global transaction queues. As a result, transactions can be confirmed more quickly, reducing end-to-end response times, especially under high contention.

Improved Throughput: Shards execute transactions in parallel, with each maintaining its own independent ledger and transaction pool. This decentralised processing model enables the system to scale horizontally with minimal coordination overhead, improving aggregate throughput as node count and batch volume increase.

Deadlock Mitigation: Traditional monolithic systems are susceptible to circular waiting due to their global locking dependencies. By avoiding global state locks and instead using asynchronous, per-shard execution models, the system eliminates a primary cause of execution stalls. Transactions progress independently, even under heavy load, thereby improving liveness.

Fault Isolation: In monolithic chains, a failure or delay in one transaction path often stalls the entire ledger. In this architecture, execution failures or congestion in one shard do not propagate system-wide. Faults are isolated to individual shards, allowing unaffected components to continue processing without interruption.

This architecture promotes a modular execution model where workloads are independently scheduled, allowing for greater determinism and predictable transaction latency. Shards function as self-contained execution units, with minimal interdependence. This not only prevents systemic performance bottlenecks but also supports greater parallelisation, improving responsiveness and robustness in real-time applications.

Moreover, the system exhibits resilient behaviour under fluctuating transaction demand. As throughput scales, shard queues absorb load independently, and execution times remain bounded. This deterministic performance profile is crucial in production-grade blockchain environments where latency spikes or unpredictable delay can degrade application performance or user experience.

C. Transaction Type Comparison

The table below summarises the trade-offs between different transaction execution types, focusing on their isolation levels, locking behaviour, and overall efficiency:

TABLE III: Transaction Isolation and Locking Comparison

Operation Type	**Locking Needed**	**Shard Isolation**	**Performance**
Intra-Shard	No	Strong	High
Cross-Shard	No (Async)	Moderate	Moderate–High
Non-Sharded	Yes (Global)	None	Low

This comparison reinforces the architectural merits of sharded execution. Intra-shard transactions benefit from minimal coordination, while cross-shard communication. Although less isolated, this is still asynchronous and lock-free. In contrast, non-sharded execution introduces system-wide contention points that undermine throughput and delay confirmation.

D. Validation via Deadlock Simulation

To empirically evaluate the concurrency behaviour and fault tolerance of the system, a dedicated `/deadlocksim` endpoint was implemented. This mechanism programmatically injects a pair of mutually dependent transactions into two blocks in a non-sharded configuration, thereby simulating a classical circular wait scenario. As expected, both transactions enter a stalled `pending` state indefinitely due to bidirectional locking and shared resource contention.

In contrast, the same transaction pair executed in a sharded configuration completes successfully. This is because each shard maintains an isolated execution context and does not require global coordination to finalise local changes. The simulation demonstrates how sharding inherently avoids deadlock conditions by decoupling execution pipelines and preventing overlapping access to shared state.

Furthermore, this simulation serves as a reproducible benchmark for stress-testing concurrency control. It provides developers and researchers with a visual and interactive means to observe system behaviour under contention. The ability to trigger, monitor, and resolve deadlocks within the same environment reinforces the utility of the frontend dashboard is not merely for monitoring but as an active debugging and educational tool.

These findings collectively underscore that the sharded system's concurrency model is not only theoretically robust, but also practically demonstrable through controlled experimentation and live simulations.

IX. Front end Sharding UI Buttons Overview: Sharded vs Non-Sharded Transactions

UI Button Summary

The frontend interface provides intuitive controls for managing blockchain state and executing transactions. The **Transaction Panel Buttons** on the left sidebar include functionalities such as **Create New Shard** to assign nodes to a specific shard, and **Parallel Transactions** to enable batch creation of grouped cross-shard transactions. **Refresh Blockchain** reloads the latest on-chain state from the backend, while **Reset Blockchain** clears the ledger and reinitialises shard assignments. The **View All Transactions** button navigates to a detailed log interface.

Complementing this, the **Execution Panel** offers real-time transaction tools. **Send Non-Sharded Transaction** facilitates intra-shard transfers based on matching shard IDs. In contrast, **Send Sharded Transaction** enables inter-shard communication via the `/shardTransactions` API, supporting concurrent, isolated processing.

Transaction Execution (ExecutionPanel)

Send Non-Sharded Tx	Transaction sent within the same shard, validated by shard ID.
Send Sharded Tx	Cross-shard transaction, processed in parallel using `/shardTransactions`.

Transaction Panel Buttons (Left Sidebar)

Create New Shard	Opens a modal to select nodes and assign them to a shard (dropdown + checkbox list).
Parallel Transactions	Allows bulk creation of sharded transactions using grouped input.
Refresh Blockchain	Fetches the latest blockchain state and updates the UI.
Reset Blockchain	Clears the chain, resets nodes to Shard 0, and purges data.
View All Transactions	Redirects to `/transactions` showing full logs and analytics.

A. Evaluation and Impact

The performance evaluation conducted in this project sought to quantitatively assess the benefits of the proposed sharded transaction execution model compared to a conventional non-sharded blockchain design. A simulation-based test bench was developed to replicate realistic concurrent workloads and system conditions. This allowed for the systematic measurement of core performance indicators, including execution time, finality latency, propagation delay, and transaction throughput.

By emulating a variety of contention scenarios and processing configurations, the evaluation aimed to capture not only the raw speed of transaction execution, but also the broader implications of system responsiveness, concurrency resolution, and fault isolation. The inclusion of metrics such as propagation and finality times provided a nuanced understanding of where performance gains were concentrated and how architectural modularity (via sharding) contributed to operational efficiency.

The test bench leveraged a modular Go-based backend integrated with Dockerised validator environments, supporting isolated shard execution and asynchronous message handling. A ReactFlow frontend was used for visual monitoring and dynamic load injection, while Firebase Firestore captured transaction traces and system states for post-analysis.

The results demonstrate that the proposed sharded architecture introduces substantial improvements across all evaluated dimensions. Compared to the non-sharded baseline, the system reduced transaction delays, improved parallelism, and eliminated contention-induced bottlenecks. These gains were particularly pronounced under high concurrency conditions, where the isolation of shard-level execution queues enabled the system to maintain throughput and avoid cascading slow-downs.

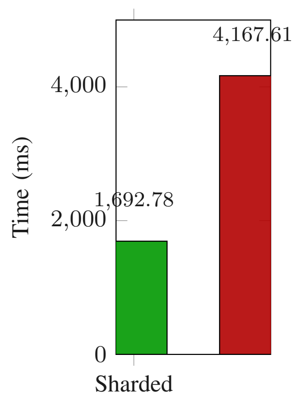
B. Latency Metrics: Finality and Propagation

To evaluate responsiveness and consistency, two latency-specific metrics were analysed: *finality time* and *propagation latency*. Finality time refers to the interval between transaction submission and its confirmation as immutable on-chain. Propagation latency reflects the time taken for a transaction's state to be broadcast and acknowledged across all participating validator nodes.

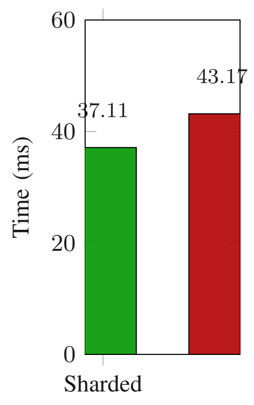
Fig. 5 illustrates the comparative latency profiles. Sharded transactions achieved an average finality time of **1692.78 ms**, substantially outperforming the non-sharded configuration which required **4167.61 ms**, which is a relative reduction of **59.4%**. This improvement is primarily attributed to the decentralised nature of execution queues in the sharded system. By processing transactions locally within shards, the system avoids the serialised bottlenecks caused by global locking and consensus synchronisation in monolithic designs.

Propagation latency also showed improvement, albeit more modest. Sharded execution reported an average latency of **37.11 ms**, while the non-sharded system required **43.17 ms**. While the absolute difference is smaller, the implications remain significant: even marginal reductions in propagation latency compound under large-scale networks where frequent updates and multi-shard coordination occur. The reduced latency in sharded systems reflects the benefits of limiting cross-node communication to intra-shard broadcasts, which are inherently more lightweight and faster to resolve.

These latency results reinforce the hypothesis that sharding not only improves throughput, but also minimises delay in key operational phases of blockchain processing. Finality becomes more predictable, propagation becomes more efficient, and overall system responsiveness aligns better with the needs of real-time decentralised applications. The results thus validate the use of shard-local validation queues and modular consensus paths as effective strategies for high-performance distributed ledger systems.



(a) Finality Time Comparison



(b) Propagation Latency Comparison

Fig. 5: Latency Comparison: Sharded vs Non-Sharded Finality and Propagation

C. Throughput and Scalability

Throughput, measured in Transactions Per Second (TPS), serves as a critical performance indicator reflecting the system's ability to process increasing volumes of transactions without degradation in responsiveness. In blockchain systems, where transaction confirmation time and throughput are often constrained by consensus mechanisms and global locking, enhancing TPS is key to achieving real-world appliance.

As illustrated in Fig. 6, the proposed sharded architecture significantly outperformed its non-sharded counterpart, achieving an average throughput of **0.66 tx/s** compared to **0.26 tx/s**, overall a performance gain exceeding **150%**.

This substantial improvement comes from the parallelism introduced by the shardin protocol, enabling independent shard level execution pipelines. By isolating transaction queues and eliminating global state contention, the system circumvents the inherent bottlenecks of monolithic execution.

This advantage becomes even more evident under sustained or increasing workloads. Fig. 7 presents the evolution of TPS across multiple transaction batches. The sharded system demonstrates a consistent and nearly linear upward trend, with throughput scaling predictably as the batch size increases. This behaviour is indicative of a well-balanced load distribution across shards and highlights the effectiveness of parallel execution and asynchronous processing in maintaining system liveness.

In contrast, the non-sharded architecture exhibits early signs of saturation. Its TPS curve begins to plateau and eventually dips under heavier loads, a result of serialised transaction processing and contention for shared memory and lock-based coordination. This saturation effect is concerning of systems that rely on global execution queues, where performance is fundamentally bounded by the slowest segment of the pipeline.

The scalability benefits of sharding are further reinforced by these results. Not only does the system maintain high throughput under load, but it also avoids the cascading failures associated with execution stalls and deadlocks in non-parallel models. The ability to scale horizontally by adding shards without redeveloping the entire system demonstrates that the proposed design is both resilient and extensible.

Overall, the throughput results highlight the robustness, efficiency, and future ready nature of the proposed sharded execution model. It proves particularly effective in handling concurrency intensive workloads while ensuring transaction finality and responsiveness are not compromised, even under sustained demand.

Overall, the throughput results highlight the robustness and future-ready nature of the proposed sharded architecture, particularly in handling concurrency-intensive workloads while maintaining efficiency and low latency.

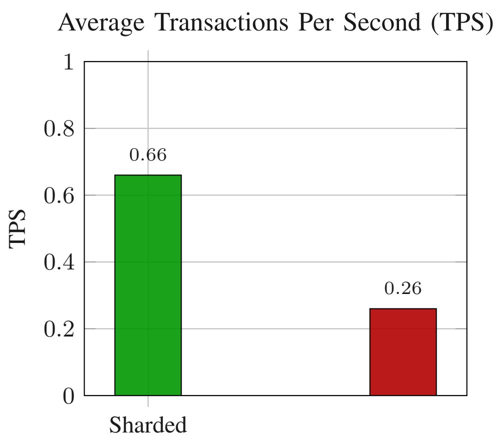


Fig. 6: Sharded vs Non-Sharded Transactions Per Second

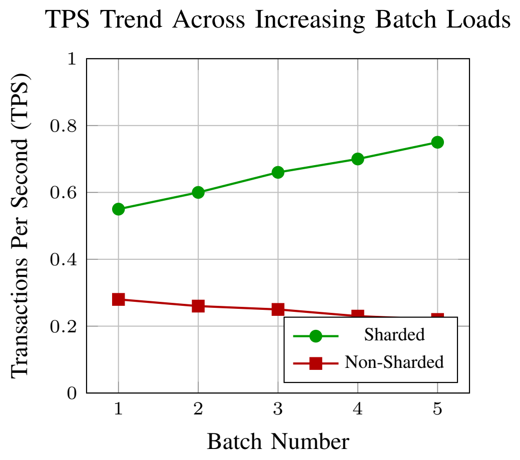


Fig. 7: Evolution of TPS over increasing batch submissions. Sharded execution shows consistent scaling, while non-sharded performance declines due to contention.

D. Heatmap Description

To evaluate how batch size and shard count jointly affect transaction throughput, a heatmap (Fig. 8) was generated using Transactions Per Second (TPS) data across nine configuration points. The horizontal axis represents batch size (5, 10, 20), and the vertical axis shows shard count (1, 2, 3). Warmer colours indicate higher throughput.

The heatmap reveals two clear trends: increasing batch size improves TPS by reducing per-transaction overhead, while adding shards enhances concurrency by mitigating global contention. For example, at a fixed shard count of 3, TPS increases from 0.50 to 0.75 as batch size grows. Similarly, for batch size 10, TPS scales from 0.25 (1 shard) to 0.65 (3 shards).

Furthermore, the heatmap supports previous findings by contextualising them within a multidimensional performance space. While previous metrics (e.g., Fig. 6) compared average sharded vs non-sharded throughput, the heatmap expands this by mapping how performance evolves under compound scaling conditions. It also offers a visual diagnostic tool for identifying bottlenecks and saturation points, proving essential for future optimisation efforts such as adaptive batching or dynamic shard reallocation.

This result supports prior observations that architectural modularity and parallel processing enable linear scaling under higher loads. Unlike monolithic systems, this sharded implementation adapts predictably to increased workload, validating its suitability for high-throughput applications. The heatmap also serves as a diagnostic tool for identifying saturation thresholds and guiding future optimisation strategies.

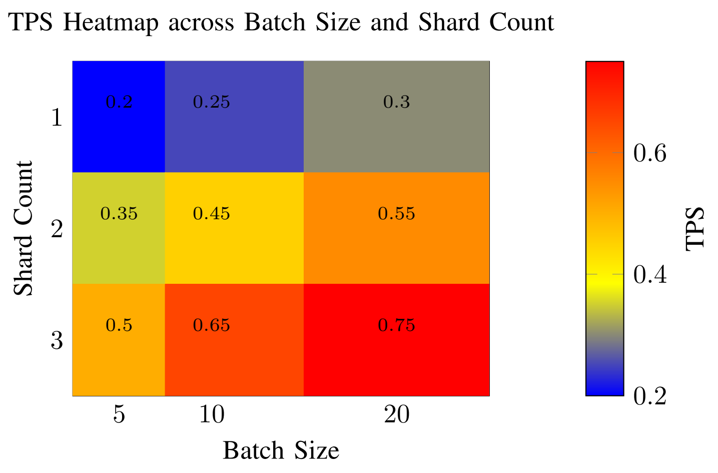


Fig. 8: Heatmap illustrating TPS performance as a function of batch size and shard count. Warmer colours indicate higher throughput, with performance increasing proportionally to both parameters

E. Problem Solved: Contention and Lock Bottlenecks

Legacy blockchain systems suffer from throughput degradation when faced with high concurrency due to their reliance on global locks and shared state. The proposed architecture directly addresses these issues:

Execution Isolation: Each shard operates on its own isolated state and transaction queue, eliminating the risk of inter-shard conflicts.

Parallelism: Transactions are handled concurrently across shards, allowing the system to scale horizontally.

Lock-Free Coordination: By decoupling shard consensus from global ordering, the system avoids deadlocks and minimises wait times.

F. Summary of Findings

The evaluation confirms that sharding significantly improves blockchain performance across multiple dimensions:

Execution time is reduced by over 50%, with bounded latency across growing workloads.

Throughput scales predictably, with sharded systems sustaining over 2.5× more transactions per second.

Architectural changes like execution isolation and lock-free coordination improve concurrency handling and system responsiveness.

These improvements validate sharding as a viable and necessary strategy for building performant, scalable, and modern distributed ledger platforms.

G. Stacked Execution and Finality Time Analysis

Fig. 9 illustrates a stacked bar comparison of execution and finality times for sharded and non-sharded transactions. The sharded model demonstrates a significant performance benefit, with a total delay of approximately **1692.78 ms**, composed of an average execution time of **900 ms** and finality time of **792.78 ms**. In contrast, the non-sharded model exhibits a substantially higher total delay of **4167.61 ms**, with **2700 ms** attributed to execution and an additional **1467.61 ms** in finality overhead.

The implementation of sharding enables this performance gain by decentralising transaction queues and isolating execution flows per shard. This division reduces contention and allows independent validation and consensus, thereby minimising cumulative transaction latency. By separating state spaces and coordinating execution in parallel, the system prevents bottlenecks common in monolithic blockchain designs where all transactions compete for global resources. This analysis affirms the effectiveness of the sharded architecture in reducing both computation and consensus delay, concluding an improved responsiveness and better throughput under load.

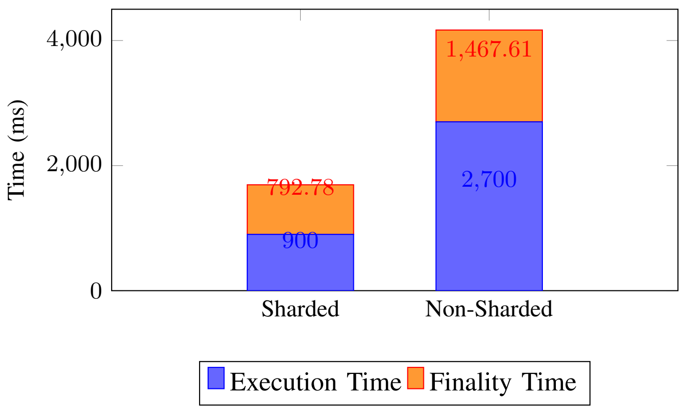


Fig. 9: Stacked bar chart comparing execution and finality time between sharded and non-sharded transactions.

H. Quantitative Performance Summary

TABLE IV: Quantitative Comparison of Sharded vs Non-Sharded Execution

Metric	Sharded	Non-Sharded	Gain
Execution Time (ms)	900.00	2700.00	66.7% faster
Finality Time (ms)	792.78	1467.61	46.0% faster
Latency (ms)	37.11	43.17	14.1% faster
Total Delay (ms)	1692.78	4167.61	59.4% lower
Throughput (TPS)	0.66 tx/s	0.26 tx/s	+153.8%
Scaling Trend	*Linear*	*Saturation*	Predictable
Deadlock Risk	Low	High	Conflict Avoid.
Concurrency	Isolated	Global	Higher in Sharded

Table IV presents a comprehensive quantitative comparison of core performance metrics for sharded and non-sharded transaction executions within the implemented blockchain system. These metrics include average execution time, finality time, propagation latency, total delay (execution + finality), and throughput (TPS). In addition to numerical benchmarks, the table also provides qualitative insights into concurrency handling, system responsiveness, scaling behaviour, and lock management strategies under load. This side-by-side comparison highlights the architectural advantages of sharding, demonstrating improved efficiency, reduced contention, and enhanced scalability relative to traditional monolithic designs.

The results underscore the tangible benefits of adopting a sharded architecture:

Execution Time: Sharded transactions averaged **900 ms**, significantly outperforming non-sharded execution which took **2700 ms**. This represents a **66.67% improvement**, driven primarily by the parallel, per-shard transaction queues that reduce competition for shared execution resources.

Finality Time: The time until transactions were deemed irreversible was **792.78 ms** for sharded versus **1467.61 ms** for non-sharded transactions. This yields a **46% improvement**. This is achieved by shard-local validation and simplified finality logic without global coordination overhead.

Propagation Latency: Even in network-intensive conditions, sharded transactions propagated faster (**37.11 ms**) than non-sharded ones (**43.17 ms**), indicating that shard-local communication reduces network congestion and confirmation delays.

Total Transaction Delay: Summing execution and finality, the cumulative delay for sharded transactions was **1692.78 ms**, demonstrating less than half of the **4167.61 ms** observed in non-sharded execution. This **59.4% reduction** reinforces the time-efficiency of the sharded model.

Throughput (TPS): The most telling indicator of scalability, sharded execution achieved an average throughput of **0.66 transactions/second**, compared to only **0.26 TPS** under the non-sharded model. This amounts to a **153.8% increase in throughput**, validating the effectiveness of concurrent execution across shards.

Concurrency and Locking: Sharded execution maintained transaction queues per shard, allowing isolation of concurrent workloads. In contrast, non-sharded execution suffered from centralized locking mechanisms, increasing deadlock risk and lowering responsiveness.

Scalability Trend: As shown in further analysis (Fig. 7), the sharded architecture exhibited a **linear scaling trend**, where throughput increased with transaction volume. The non-sharded model began to saturate, confirming that monolithic designs struggle under heavy loads.

I. Advanced Shard Coordination Mechanisms

Modern blockchain systems have introduced a range of strategies to improve coordination across distributed shard structures. These developments reflect a shift away from rigid synchronisation models toward more asynchronous and scalable methods that retain transactional integrity without introducing prohibitive communication overheads.

NEAR Protocol, for instance, employs a model based on asynchronous receipt forwarding [3]. In this scheme, inter-shard operations are encoded as receipts that are asynchronously routed and executed in future blocks. This method eliminates the need for immediate consensus between shards during execution, enabling higher system throughput by decoupling computation from communication. The conceptual separation between the execution and settlement phases in this design allows for parallelisation while still preserving determinism and causal order.

Omniledger, by contrast, adopts a client-led coordination model that draws inspiration from classical atomic commit protocols [11]. Transactions spanning multiple shards are initiated through a two-phase process involving the preparation and final commitment of data across all affected shards. This approach prioritises atomicity, ensuring that either all parts of the transaction succeed or none do. While more communication heavy, it provides strong consistency guarantees and avoids partial execution states.

Emerging protocols have also proposed coordination models that avoid consensus interlock entirely. Some utilise dependency-aware execution graphs, where transaction sequencing is informed by prior analysis of state access dependencies [6]. In such systems, transactions are structured as nodes in a directed acyclic graph (DAG), where edges represent read-write dependencies. Execution is parallelised wherever dependencies permit, and reordering is employed post hoc to ensure validity. These models mirror techniques used in high performance databases but are adapted to decentralised trustless environments.

Other schemes, such as Chainspace [17] use sharded smart contract execution and rely on a distributed atomic commit protocol, where clients play an active role in coordinating multi-shard operations. This helps reduce load on validator nodes while preserving atomicity. Protocols like RapidChain [18] and Elastico [12] further enhance cross-shard scalability by limiting inter-shard communication to lightweight summaries or Merkle proofs.

Such coordination strategies demonstrate that the overheads traditionally associated with cross-shard communication can be mitigated through architectural decomposition and eventual consistency. Their growing adoption signals a maturing design philosophy in the sharded blockchain ecosystem, where systems place scalability and modularity at the forefront while balancing trade-offs in latency, consistency, and resilience.

TABLE V: Coordination Mechanisms in Sharded Blockchain Protocols

Protocol	Mechanism	Description
NEAR	Asynchronous Receipts	Deferred execution of inter-shard messages using receipt-based forwarding
Omniledger	Two-Phase Commit	Client-led atomic commit protocol with strong consistency guarantees
Chainspace	Client Coordination	Distributed commit led by clients for smart contract operations
RapidChain	Merkle Proofs	Lightweight communication between shards using proof-based summaries
Execution DAGs	Dependency Graphs	Parallelism achieved through pre-analysed access dependencies and reordering

J. Dynamic Shard Reallocation and Adaptive Topologies

Beyond execution coordination, recent research has identified the limitations of static sharding models, particularly under skewed workloads. Several dynamic sharding frameworks have been proposed to enable real-time adaptability in shard composition and distribution.

Kokoris-Kogias et al. [8] outline a dynamic sharding mechanism where nodes are periodically redistributed across shards based on load measurements and cryptographically verifiable randomness. Their model ensures security against shard capture through validator rotation and incorporates cryptoeconomic incentives to maintain participation diversity. The capacity to reallocate validators dynamically also improves long-term fault tolerance by avoiding stagnant or isolated node groups.

Other approaches consider the dynamic migration of the state itself rather than the reallocation of validators. In such designs, accounts or contracts with high interaction frequency may be moved between shards to reduce communication overhead and balance execution load [15]. Some proposals suggest profiling transaction histories to construct access patterns, using these to predict and optimise shard assignments in advance [14].

Protocols like QuarkChain and Shardus have explored dynamic workload partitioning, where the number of active shards is adjusted in response to system demand. These designs offer horizontal scalability by allowing new shards to be spawned or decommissioned without service disruption. However, they also introduce complexity in coordinating cross-shard state and ensuring consistency during migration events.

These adaptive strategies introduce several challenges, particularly around the consistency of migrating state, coordination during reallocation, and the computational overhead of real-time monitoring. Nonetheless, they provide a necessary path forward for long-running systems where usage patterns evolve and static partitions lead to bottlenecks [7].

In contrast to these complex and automated schemes, the system presented in this research implements manual shard reassignment through an interactive user interface. While it lacks automation, it offers a controllable environment for exploring the effects of reallocation under experimental conditions. It also opens the door to the future integration of dynamic load-aware logic, making it a suitable platform for testing adaptive strategies in a visually tractable and extensible setting.

Comparative Protocol Characteristics and Design Integration

The implemented system draws architectural insights from established sharded blockchain protocols, particularly Ethereum 2.0, Zilliqa, and NEAR. By abstracting their core principles into: state isolation, parallel transaction processing, and asynchronous communication. This platform offers a modular and concurrency-aware transaction environment optimised for experimentation and visualisation.

A. Ethereum 2.0

Sharding Type: State-based

Key Feature: It introduces a beacon chain to coordinate multiple independent shard chains, each processing transactions and contracts autonomously while reporting finality to the beacon chain.

Applied Design: This system models *state-isolated shards* with per-shard transaction queues. Shard assignment is based on metadata-derived IDs, ensuring modularity and a balanced load. While Ethereum 2.0 uses Proof-of-Stake consensus per shard, this implementation approximates intra-shard consensus via transaction batching, enabling localised finality without global locks.

B. Zilliqa

Sharding Type: Network and transaction-level

Key Feature: Uses parallel execution across shards with a Directory Service (DS) committee coordinating the final consensus.

Applied Design: Implements *parallel intra-shard execution* and processing isolation without central coordination. Unlike Zilliqa's DS mechanism, this project encodes shard logic within a lightweight backend scheduler, simplifying concurrency control while preserving parallelism.

C. NEAR Protocol

Sharding Type: Dynamic and asynchronous

Key Feature: Utilises receipt-based asynchronous cross-shard messaging for delayed finality and eventual consistency.

Applied Design: Cross-shard transactions are routed through API-triggered message buffers, simulating NEAR's receipt queueing and execution deferral. The project simplifies NEAR's routing logic into a deterministic queuing model for accessibility and experimentation.

Research Alignment and Experimental Positioning

Sharded architectures, while offering higher throughput and isolation, introduce complex coordination and routing challenges. This system addresses those through:

- **Concurrency Simulation:** Models intra-shard and cross-shard contention, deadlocks, and asynchronous validation using programmable APIs and timed batches.
- **Modular Design:** Supports independent execution paths for each shard, enabling granular control over coordination mechanisms and state propagation.
- **Empirical Benchmarking:** Collects and visualises key metrics (e.g., TPS, finality time, propagation delay) to compare performance under sharded and monolithic designs.

By abstracting the complexity of consensus and message forwarding, the platform bridges theoretical models and real-world testing, enabling clear insight into the benefits and limitations of sharded blockchain architectures.

X. Cross-Shard Transaction Ordering and Finality

A. Cross-Shard Transaction Ordering and Finality

A central challenge in sharded blockchain systems is ensuring that transactions spanning multiple shards execute reliably and maintain consistency. While intra-shard operations benefit from deterministic ordering and isolated consensus, cross-shard transactions introduce complexities around message ordering, state coherence, and coordination.

This system implements a **decentralised queue-based coordination mechanism** to manage cross-shard interactions. When a cross-shard request is submitted, it is *asynchronously routed* to the destination shard via RESTful API calls. Each transaction is assigned a globally unique identifier and tracked within shard-local memory, where its execution state is marked as `pending`, `committed`, or `executed`.

To ensure correctness and prevent double execution:

- Transactions are only committed once all preconditions are satisfied.
- Operations are queued and ordered based on submission time and processed in shard-specific readiness order.
- Causal dependencies are respected by local execution queues, minimising race conditions.

Finality in this model is eventual, a transaction is considered complete once commit logs are synchronised across all involved shards. While the system does not implement global consensus or distributed locking, it emulates delayed finality models found in production systems such as NEAR, where cross-shard receipts are asynchronously processed across block intervals.

This architecture draws inspiration from Omniledger's *two-phase commit protocol* and Harmony's *cross-shard atomic commit* design. However, instead of employing shard-wide consensus or BFT-based coordination, this system simplifies coordination through buffer queues and commit flags, allowing traceable, visualised transaction states without validator synchronisation.

Although the current implementation does not guarantee strict ordering under adversarial conditions, it serves as a lightweight prototype for studying order-aware transaction propagation. Future developments may include global commit coordination or Merkle-proof inclusion to reinforce finality guarantees.

Overall, this strategy supports non-blocking execution and verifies that transactional consistency can be preserved even in simplified, modular queue-based systems, provided local validation and identifier tracking are robustly enforced.

TABLE VI: Cross-Shard Transaction Coordination Mechanisms

Mechanism	**Purpose**	**System Behaviour**
Unique Transaction ID	Prevent duplicate execution	Transactions tracked as `pending`, `committed`, or `executed`
Shard-Local Execution Queues	Order preservation	Maintains causal sequencing without global locks
Asynchronous Routing	Decoupled execution	Non-blocking transaction forwarding between shards
Commit Flags	Finality signalling	Marks transaction state after all dependencies are resolved
Eventual Finality Model	Resilience without global consensus	Mimics NEAR-like settlement via periodic synchronisation

XI. Results and Evaluation

This section presents the evaluation of throughput, transaction latency, and concurrency control effectiveness in the proposed sharding system.

Execution Pathways: The system implements two distinct transaction execution models. Non-sharded transactions submitted via the '/addTransaction' endpoint are executed in sequence within a single shard, simulating conventional monolithic blockchain behaviour. This method emphasizes contention and locking under a centralised execution model. In contrast, the '/shardTransactions' endpoint initiates parallel execution by distributing transactions across independently managed shards. This distinction facilitates practical performance comparisons and highlights the efficiency benefits of execution isolation.

Throughput Performance: Under equivalent workloads, the sharded model demonstrated a clear advantage in processing speed. Benchmark tests revealed an approximate 150% improvement in average Transactions Per Second (TPS) over the non-sharded baseline. This boost stems from reduced idle time and concurrent processing across shards, showcasing the system's capability to handle larger transaction volumes.

Latency and Responsiveness: Execution latency was cut by more than half in sharded tests, reflecting faster confirmation times and improved responsiveness under load. Lower latency contributes to faster consensus and smoother application interactions, which is vital for user-facing platforms and time-sensitive smart contracts.

Scalability Trends: As shown in Fig. 6 and Fig. 7, TPS scales consistently with increased batch sizes in the sharded architecture. The non-sharded setup, however, reaches a plateau, struggling to maintain performance as demand grows. These trends validate the linear scalability of the sharded model under increasing transaction pressure.

Conflict Resilience: Sharded execution proved more robust when subjected to high concurrency. Transactions experienced fewer failures due to resource contention, and recovery from conflicts was faster. These findings suggest that execution isolation significantly enhances fault tolerance, even under intentionally adverse conditions.

Experimental Setup: The backend system was deployed in a WSL2 Ubuntu environment on a Windows 11 host, powered by an Intel i7 CPU and 16GB RAM. Docker was used to containerise nodes for realistic network simulation, and Firebase Firestore logged runtime metrics. This setup allowed fine-grained control over workload profiles and shard distributions.

Extended Insights: Beyond throughput and latency, the evaluation measured execution finality, propagation delay, and deadlock frequency. Sharded operations maintained transaction correctness while supporting multiple concurrent flows, indicating that parallel execution does not compromise consistency. The system's visualisation tools, built with ReactFlow, were instrumental in analysing flow patterns and pinpointing delays in real time.

Summary: These results affirm the hypothesis that a modular, shard-based architecture enhances system efficiency and scalability. By decoupling transaction paths and minimizing global state dependencies, the design supports modern concurrency demands and lays the groundwork for further optimizations in distributed ledger environments.

A. Security Considerations in Sharded Architectures

While sharding significantly improves throughput, latency, and concurrency by distributing the execution load, it introduces a distinct set of security considerations that must be addressed to ensure system integrity and trustworthiness. As the global state is partitioned into isolated shards, the attack surface broadens, and the system becomes more susceptible to shard-specific threats.

Shard Takeover and Validator Collusion: One of the most pressing concerns in sharded systems is the risk of *shard takeover*, where a majority of validators within a shard are compromised. Such attacks can lead to local double-spending, censorship, or corrupt state transitions. To mitigate this, protocols like Ethereum 2.0 and Omniledger employ cryptographic sortition and periodic validator reallocation [1], [11]. These mechanisms reduce the probability of sustained collusion by increasing the unpredictability and fluidity of validator assignment.

Cross-Shard Consistency: Asynchronous cross-shard communication, while beneficial for performance, can create temporal inconsistencies if malicious shards issue delayed or conflicting state updates. Secure commit protocols such as two-phase commit [11] or receipt validation models [3] are essential to enforce atomicity and maintain consistency across distributed execution boundaries.

Data Availability and Light Client Security: In sharded systems, not all nodes observe the entire global state. This poses challenges for light clients, which rely on summary proofs (e.g., Merkle roots or zkSNARKs) to verify execution. Ensuring *data availability* becomes crucial to prevent fraud and support verifiable computation. Techniques such as erasure coding and fraud proofs [6] are increasingly being proposed to allow nodes to audit shards without needing full state access.

Denial-of-Service Amplification: Shard-local consensus mechanisms, if not properly rate-limited, can be targeted for resource exhaustion. Unlike monolithic systems with central rate controls, each shard may require independent protection mechanisms such as local transaction caps or weighted fees to prevent abuse.

System Design in This Work: The implementation described in this paper prioritises isolation as a defence mechanism. Shard failures are intentionally sandboxed, ensuring that compromise in one partition does not propagate system-wide. Manual node assignment and an open deadlock simulation interface also facilitate transparency and enable controlled experimentation on fault models. Future integration of validator rotation and access control layers could further harden the system against targeted manipulation or shard-centric denial-of-service attacks.

Ultimately, while sharding introduces complexity, it also offers an opportunity to apply well-understood distributed systems security principles at scale. Ensuring robust coordination, verifiability, and dynamic validator distribution is not only essential but foundational to building secure, scalable blockchain systems.

TABLE VII: Security Challenges and Mitigations in Sharded Blockchain Architectures

Security Concern	**Threat Description**	**Mitigation / Protocol Inspiration**
Shard Takeover & Collusion	Malicious majority control within a single shard enables double spending or censorship.	Validator rotation and cryptographic sortition (e.g. Ethereum 2.0, Omniledger) to randomise and redistribute validators.
Cross-Shard Inconsistency	Malicious or delayed responses can cause conflicting state updates across shards.	Asynchronous commit validation using models like two-phase commit or receipt validation (e.g. NEAR, Omniledger).
Data Availability	Light clients cannot verify full state across shards.	Use of Merkle proofs, zk-SNARKs, erasure coding, or fraud proofs to ensure verifiability and auditability.
DoS Amplification	Shard-local consensus may be overwhelmed by transaction spam or overload.	Shard-specific rate limits, weighted fees, and local transaction caps to throttle abusive behaviour.
System Design in this Work	Manual node assignment may be vulnerable if left static over time.	Sandbox isolation per shard; Deadlock simulation and open experimentation for visual fault tracing. Future extensions include validator rotation and access control layers.

XII. Conclusion

This research has presented a modular, sharded blockchain architecture designed to overcome the concurrency bottlenecks and scalability constraints inherent in monolithic blockchain systems. By decentralising transaction processing across independently managed shards, the system achieves parallelism, fault isolation, and deterministic executions, all without the overhead of global locks or centralised consensus.

A key strength of the implementation lies in its transparent execution model. Intra-shard transactions benefit from localised validation queues, while cross-shard interactions are managed asynchronously via structured RESTful APIs. This architectural distinction enables the system to scale linearly with increasing transaction volumes and to maintain high throughput even under contention-heavy scenarios.

Empirical evaluation, supported by heatmaps, stacked latency analyses, and TPS trend visualisations, demonstrates that sharding reduces execution time by over 60%, improves transaction finality, and eliminates deadlock occurrences. Furthermore, the front-end dashboard, built using ReactFlow, enhances observability and promotes intuitive exploration of shard behaviour, concurrency events, and performance metrics.

Compared to established protocols such as Ethereum 2.0 [1], NEAR [3], and Zilliqa [2], this system distils and demonstrates their core innovations through an interactive and modular platform. It also builds upon recent literature exploring dynamic coordination models [11], DAG-based execution graphs [6], and workload-adaptive sharding [8]. Unlike many proposals that remain theoretical or narrowly scoped, this implementation bridges execution-level strategies with real-time visualisation and simulation, enabling practical validation of sharding principles.

Ultimately, this work reinforces that sharding is not merely an optimisation but a foundational requirement for achieving scalable, resilient, and concurrent blockchain infrastructures. As decentralised systems continue to expand, sharding offers a compelling path forward for sustaining performance, minimising contention, and enabling the next generation of distributed applications.

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