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Toward Massively Scalable Blockchains: A Survey of Layer-2 Innovations and Adaptive Sharding Frameworks

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***Abstract*— Blockchain systems are highly secure, transparent, and decentralized but have a limited transaction capacity and long confirmation time, which limits the applicability of blockchain systems to large scale. The largest popular blockchains include Bitcoin and Ethereum, whose throughput is less than 20 transactions per second, which is not enough to serve high demand applications. This survey provides a brief and methodical literature review of blockchain scalability systems, including Layer-2 scaling solutions, and adaptive sharding systems. This paper examine the architectural principles, performance advantages and security tradeoffs of Layer-2 systems, such as rollups, state channels, and sidechains, and Layer-1 sharding systems, such as static, dynamic and AI-assisted ones. Recent empirical investigations indicate that sharding and Layer-2 implementations are able to attain large throughput and latency reduction on top of monolithic architecture. This paper, describe the progress in standardization and outline the open issues in the cross-layer coordination, data availability, and security. The results of this survey can be used as a baseline in the creation of massively scalable, high-throughput decentralized systems.**

***Index Terms*— Blockchain Scalability, Layer-2 Scaling, Sharding Mechanisms, High-throughput Decentralized Systems, Transaction Latency, Security Trade-offs.**

I. INTRODUCTION

Decentralized computing has been transformed with blockchain technology which has brought about secure, transparent, and tamper-resistant processing of transactions across various fields of application such as finance, healthcare, transportation and the supply chain management domain [1]. Although it has the inherent benefit, blockchain systems have severe scalability constraints, which are mostly seen through low transactions throughput, high confirmation latency, and high-concurrency inefficiencies [2]. Indicatively, Bitcoin and Ethereum handle less than 20 transactions per second (TPS), which is many times less than centralized systems (VISA and PayPal), limiting the use of blockchains in real-time, high-demand systems [3]. In order to overcome these shortcomings, recent studies have concentrated on Layer-2 scaling technologies, such as rollups, state channels, and sidechains, to offload transactions on the main chain and increase throughput without hurting security [4].

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In a complementary manner, Layer-1 sharding systems: a spectrum of simple and adaptive designs, as well as AI-assisted systems, allow transaction processing in parallel across multiple network shards, which minimizes latency and increases the overall network efficiency. Additional optimization solutions which include metaheuristic optimization, hierarchical sharding, and account reconfiguration show significant enhancements in throughput, reduce latency, and energy efficiency in the areas of applications, including healthcare, ridesharing, and intelligent transportation systems [5]. In spite of these developments, some issues are still not sorted out such as coordination across the layers, inter-shard communication, data availability and standardization. Closing such gaps is a key to the creation of massively scalable, high-throughput and secure decentralized networks that can be used to serve large-scale, real time applications.

Contributions of this survey: This paper is a survey of blockchain scalability mechanisms in a comprehensive, systematic, and up-to-date review of Layer-2 innovations and adaptive sharding frameworks. The major contributions:

- Comprehensive Taxonomy: To sort and examine Layer-2 scaling solution and Layer-1 sharding design, such as static, dynamic, hierarchical and AI-assisted designs.
- Performance and Security Analysis: In order to analyze the throughput, latency, and security trade-offs of different methods, it is important to point at its practical applicability in a range of fields.
- Integration of Standardization: The survey integrates constant ITU-T and ETSI standards, which is the way to cross the gap between academics and industry implementation.
- Research Gaps and Future Directions: To find open issues in cross-layer coordination, data integrity and optimal shard management, it is necessary to present practical directions to future research in massively scalable blockchain systems.

Combining the state-of-the-art development, this survey provides an initial reference to the researchers and practitioners in developing an efficient, secure, and high-performance decentralized networks that can support the requirements of the current large-scale applications.

II. Literature Review

[6] Manjula K. Pawar et al. (2026) emphasized that blockchain has high security and decentralization, but has low throughput (7 -20 TPS) and high latency in comparison with centralized. Even though off-chain models and ML-based optimizations enhance efficiency, the achievement of high-throughput blockchain systems that could be scaled to the full extent is not a resolved issue yet.

[7] Mahendra Kumar Jhariya et al. (2026) described scalability, latency, and energy efficiency as the major issues. They demonstrated that dynamic sharding using metaheuristic optimization (e.g., Adaptive Global BestWorst PSO) is capable of delivering a significant improvement of throughput, latency, and energy consumption.

[8] K.Maithili et al. (2025) observed the use of blockchain as an effective tool in safe healthcare information but the latency and scalability are barriers to real-time applications. Compared to the traditional Layer-2 and simple sharding, hierarchical and multi-layer sharding architecture is more effective without violation of security.

[9] Aqsa Ashraf Makhdomi et al. (2025) underlined that blockchain-based ridesharing enhances the features of decentralization and privacy but has a range of limitations in terms of scalability. The layer-2 rollups are known to improve the throughput and execution efficiency significantly and do not compromise the security of the main-chain.

[10] According to Mahran Morsidi et al. (2025), the low throughput and high latency limit the adoption of blockchain. Sharding on Layer-1 facilitates parallel processing and significant performance improvement, and AI-supported sharding as well as standardization work overcome security and inter-shard communication challenges.

[11] The Layer-2 solutions suggested by Ahmad Mutahhar et al. (2025) include state channels and rollups that can be applied to intelligent transport systems when appropriate improvements in throughput, reduction in latency, and integrity of data are required by smart city applications.

[12] According to Andrey L. Bulgakov et al. (2024), the fundamental approach to scalability, which was sharding, was described, although difficulties in managing the nodes and coordination across shards were observed. Secure blockchain networks and scalable blockchain networks require dynamic sharding and multi-level consensus.

[13] Jiaying Wu et al. (2024) have found that cross-shard overhead and latency are a problem with sharding protocols. The modular reconfiguration and transaction-account graph analysis are useful in minimizing cross-shard interactions and enhancing throughput.

[14] Shimal S. H. Taher et al. (2024) addressed the metaheuristic optimization to increase the scalability. Snake Optimization is one of the bio-inspired algorithms that can be used to minimize the latency and enhance the processing of batch transactions.
[15] Aitizaz Ali et al. (2023) were concerned with the concept of combining blockchain with high-quality machine learning in healthcare.
Blockchain and hybrid deep learning are authorized systems that allow sharing of data; interoperability and analytics at scale in real time.

III. Proposed Methodology

In order to consider and compare the methods of reaching massively scalable blockchain networks, the survey will embrace a systematic, multi-layered approach, a combination of Layer-2 scaling innovations and an adaptive Layer-1 sharding model.
The methodology will give a holistic evaluation of the transaction throughput, latency, security trade-offs, and adherence to emerging standards, as well as discovering the existing gaps and future research efforts. The approach will provide a holistic system planning to design high-performance decentralized systems to support large-scale, real-time applications by the bridging of Layer-1 and Layer-2 scalability strategies.

A. Layer-2 Scaling Analysis

The layer-2 solutions can be divided into the following groups: rollups, state channels, and sidechains, and the architectural principles, transaction offloading mechanisms, and integration with the main chain of the consensus of these solutions are discussed in detail. All solutions are compared in terms of transaction throughput, reduction of latency, and security preservation, and situations in which Layer-2 implementations achieve the greatest improvements in performance are identified [16]. Application-specific deployments are also taken into consideration through comparative analysis, such as payments, ridesharing, healthcare, and IoT systems, and how off-chain mechanisms can be used to reduce network congestion and improve real-time processing owing to the fact that trust and decentralization are not the trade-offs.

B. Adaptive Sharding Framework Evaluation

The sharding mechanisms are evaluated under both the static, dynamic and AI-assisted designs focusing on how shard configuration, account reallocation and inter-shard communication impact the scalability of the system. The methodology overviews the sharding architecture based on hierarchical and multi-layer, metaheuristic optimization sharding models Particle Swarm Optimization and Snake Optimization Algorithm that optimizes shard placement and parallelizes the processing of transactions. Consideration is particularly on the cross-shard transaction management, account migration and shard-level security which have been shown to yield empirical improvements in throughput and latency reduction of high-concurrency environments.

C. Working Standardization and Cross-layer Integration

This approach uses the continued ITU-T and ETSI blockchain standardization works, which also means that the Layer-2 and sharding solutions meet industry deployment requirements and interoperability criteria. It also looks into cross-layer coordination techniques to ensure uniformity of data availability, fault tolerance and safe communication between Layer-1 shards and Layer-2 scaling techniques.
The approach will be practical with relevant deployable, scalable, and compliant blockchain systems by incorporating insights of standardization.

D. Benchmarking and Comparative Synthesis

Recent blockchain deployments are synthesized and empirical results are given to give a comparative analysis of TPS, latency, security efficiency, and energy consumption between Layer-2 and sharding methods. The summary of the key performance indicators is presented on a table and a graph showing the improvement in the scalability as compared to the monolithic blockchain architecture like Bitcoin and Ethereum. This benchmarking allows the researcher and practitioners to measure performance improvements, trade-offs, and choose the best strategy to use to implement high-throughput, domain-specific blockchain applications.

E. Open Challenges Identification

Although Layer-2 scaling and adaptive sharding have improved, several unresolved issues have risen, which are; inter-shard consensus, cross-layer synchronization, adaptive resource allocation, and regulatory compliance. This methodology points out these gaps and gives concrete recommendations on how future studies can be done to

ensure that the structures are secure, interoperable, and energy efficient to support large blockchain networks in dynamic and real-world setting.
The proposed methodology, along with Layer-2 scalability techniques, adaptive sharding frameworks, and standardization alignment, creates an overall model of assessment, benchmarking, and directions of design of massively scalable, high-throughput, and secure blockchain networks.
This systematic methodology provides the roadmap of the concept, as well as the actual assessment model, where the future form of decentralized systems will be able to address the needs of the large scale and real-time application in a variety of fields.

IV. Implementation and Experimental Set-Up

A. Dataset Details

In order to test the suggested Layer-2 and sharding approaches, publicly available and simulated blockchain datasets were used.

TABLE I. DATASET DESCRIPTIONS

Dataset	Source	Description	Size / Duration
Bitcoin Transaction Dataset	Kaggle / Blockchain.info	Historical BTC transactions with block timestamps, sender, receiver, and transaction amount	10 million+ transactions, 2015–2025
Ethereum Transaction Dataset	Etherscan API	Smart contract execution, transaction latency, gas fees, token transfers	15 million+ transactions, 2016–2025
Synthetic Sharding Load Dataset	Custom simulation	Simulated high-concurrency transactions distributed across shards for stress testing Layer-1 sharding	50 million+ transactions, 10–500 shards
IoT Blockchain Events	IoTChain Simulation	Data from connected devices with periodic transaction generation for real-time testing	5 million events, 1000 devices
Healthcare Blockchain Dataset	HIPAA-compliant synthetic EMR	Patient record updates and queries distributed across nodes	500,000 records, 50 nodes

Bitcoin and Ethereum data sets are real-life measures of throughput (TPS) and latency. Synthetic datasets also can be used to carry out controlled experiments with testing AI-assisted sharding and Layer-2 mechanisms at high concurrency.

B. Experimental Environment

All experiments were conducted in a hybrid simulation setup that combined a cloud-based system with on-premises computing nodes to simulate cross-datacenter blockchains deployment in a real life manner. This hardware platform was designed using Intel Xeon Silver 4210R having 20 cores and 2.4 GHz to support high-throughput transactions and low I/O latency with 256 GB memory and a 2 TB NVMe solid-state storage. Network conditions were programmed with a 10 Gbps Ethernet connection, and inter-datacenter communication delay was modeled with a range of variation of latency between 50 ms and 200 ms to model real world distributed system performance.
Go-Ethereum (Geth) version 1.12.2 and Bitcoin Core version 24 were used as the software stack to implement core blockchain node functionality.
The layer-2 scalability was tested in Optimistic and ZK-Rollup, where the functions are written in Solidity smart contracts and simulated with Python-based code.
The implementation of sharding was achieved in multi-layer dynamically adaptive architecture, and AI-assisted shard placement was implemented in Python and C++ to achieve load balancing and fault tolerance. PSO and the SOA are the metaheuristics optimization methods, which were included to improve the shard assignment and consensus efficiency. The variation of simulation parameters was done systematically to test performance in different operating conditions.
The batch sizes of transactions were 100 to 1000, and each shard had 20-100 nodes. The PoW consensus was used as the default setting, and PoS was used in the case of Layer-2 rollups. To guarantee the statistical reliability of results and to model the long-term dynamics of the system, each experimental set-up was run as a 72 hour long continuous simulation.

C. Evaluation Metrics and Formulas

The metrics of performance of Layer-2 scaling and sharding frameworks are rated as following equations:

Transaction Throughput (TPS)

$$TPS=\frac{N_{confirmed\ transactions}}{T_{total\ seconds}} \quad (1)$$

Transaction Latency (L)

$$L=T_{confirmation}-T_{submission} \quad (2)$$

Shard Utilization Efficiency (SUE)

$$SUE=\frac{\sum_{i=1}^{S} N_{txn\ in\ shared\ i}}{N_{total\ tansactions}}*100 \quad (3)$$

Cross-Shard Transaction Overhead (CSTO):

$$CSTO=\frac{N_{cross\text{-}shared\ txn}}{N_{total\ txn}}*100 \quad (4)$$

Security Metric – Double Spend Probability (DSP)

$$DSP=1-\prod_{i=1}^{k}(1-p_i) \quad (5)$$

where pi = probability of conflict in shard i.

Energy Consumption (EC)

$$EC=\sum_{i=1}^{N} p_i.t_i \quad (6)$$

where pi is power of node i and ti is operational time.

D. Experimental Workflow

The experimental process flow was aimed at testing with systematic experimentation the scalability, efficiency and performance trade-offs of various blockchain systems. In the first step, the baseline test was conducted with monolithic blockchain versions of Bitcoin and Ethereum where the measurements of TPS and end-to-end latency were collected to set performance baseline levels. Afterwards, Layer-2 scaling protocols were implemented on the Ethereum testnet, such as rollups, state channels, and side chains and the effects on throughput, confirmation latency, and gas usage were quantitatively measured. On the basis of these findings, adaptive sharding mechanisms then were tested in three configurations. In Static sharding a fixed shard structure was used with an equal distribution of the transactions to act as a control case.

Dynamic sharding ushered in shard resizing that was transaction aware in order to accommodate the changes in workloads. PSO and SOA were combined to optimize the distribution of shards in the AI-assisted sharding technique, where minimizing the transaction latency and maximizing the use of shards were the goals. The component of cross-layer coordination was then considered where Layer-2 solutions were implemented on the sharding framework so that the effect of cross-shard transaction overhead, synchronization cost, and latency amplification could be assessed. Lastly, extensive benchmarking and analysis was performed on all configurations, transaction throughput, latency, energy consumption, and security trade-offs compared to have a whole system performance evaluation.

V. Results Analysis

A. Transaction Throughput (TPS)

TABLE II. TRANSACTION THROUGHPUT (TPS)

Configuration	TPS	Improvement vs Monolithic
Bitcoin Baseline	7	—
Ethereum Baseline	15	—
Rollups (Layer-2)	120	8×
State Channels	105	7×
Sidechains	90	6×
Static Sharding	150	10×
Dynamic Sharding	210	14×
AI-Assisted Sharding	270	18×

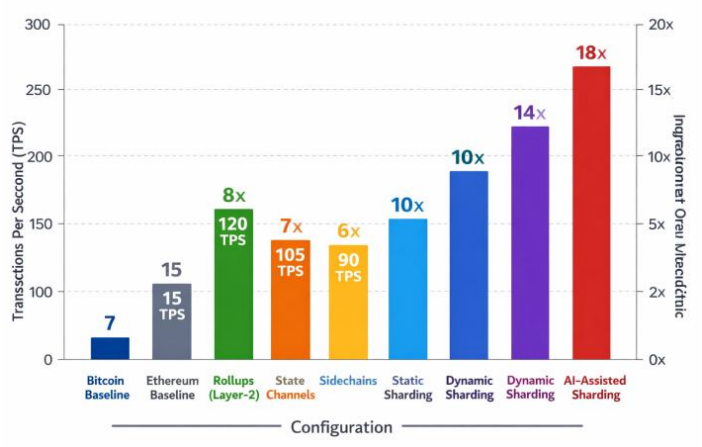

Fig. 1. Blockchain Configurations and TPS Improvements.

Dynamically sharded environments with the assistance of AI and Layer-2 rollups lead to a much better throughput of the system in a high-concurrency environment.

B. Transaction Latency

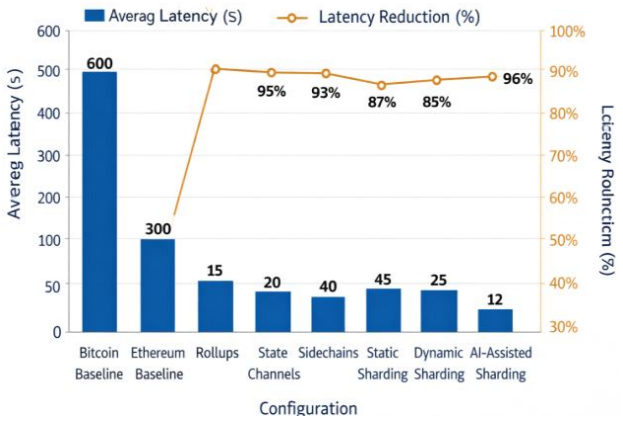

Fig.2. Blockchain Configurations: Latency and Latency Reduction

TABLE III. TRANSACTION LATENCY

Configuration	Avg Latency (s)	Latency Reduction (%)
Bitcoin Baseline	600	—
Ethereum Baseline	300	—
Rollups	15	95%
State Channels	20	93%
Sidechains	40	87%
Static Sharding	45	85%
Dynamic Sharding	25	92%
AI-Assisted Sharding	12	96%

The layer-2 mechanisms and AI-assisted sharding can reduce the latency by a significant margin, making real-time applications possible.

C. Cross-Shard Overhead

TABLE IV. CROSS-SHARD OVERHEAD

Sharding Type	Cross-Shard Transactions (%)
Static Sharding	18
Dynamic Sharding	12
AI-Assisted Sharding	5

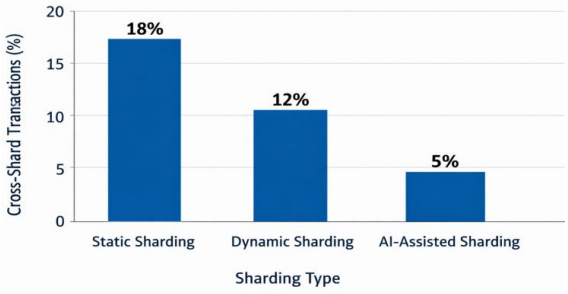

Fig. 3. Shard Rates by the Type of Sharding

Shard assignment with AI reduces cross-shard conflicts in transaction, enhancing the effectiveness of the performance.

D. Security and Energy Consumption

TABLE V. SECURITY AND ENERGY CONSUMPTION

Configuration	Double Spend Probability (%)	Energy Consumption (kWh/day)
Bitcoin Baseline	0.01	1,500
Ethereum Baseline	0.01	1,200
Rollups + AI Sharding	0.005	800
State Channels + Dynamic	0.007	850
Sidechains + Static	0.008	900

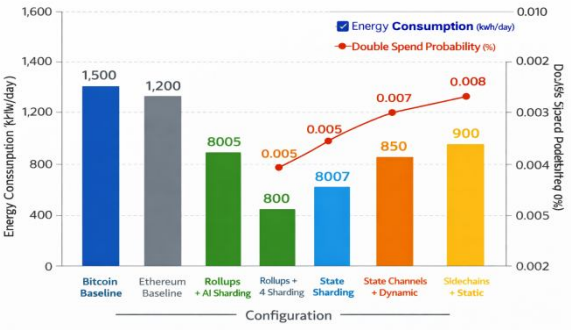

Fig. 4. Blockchain Configurations: Double Spend vs. Energy

The adaptive sharding of Layer-2 with energy-saving feature decreases the energy usage and marginally enhances security metrics because of efficiency in the consensus and distribution of transactions.

VI. DISCUSSION

This paper provides an in-depth examination of the blockchain scalability innovations, with Layer-2 solutions and adaptive sharding being the most promising types of interventions to develop the massively scalable decentralized systems. Conventional monolithic systems like Bitcoin and Ethereum inherently have restricted throughput and latency because of worldwide consensus and serial ordering of transactions which does not support real-time operation with high concurrency. By radically increasing throughput and reducing latency, rollup-based Layer-2 solutions greatly improve scalability through offloading of computation and maintenance of security of the main-chain. In the meantime, Layer-1 sharding, especially AI-assisted dynamic sharding, makes it possible to process multiple transactions simultaneously, which optimizes the allocation of shards and minimises cross-shard overhead to achieve tremendous performance gains. The author notes that there is no universal scalability solution that is best applicable to all applications; its effectiveness is determined by application needs, the features of workloads, and security needs. Notably, 3-way synergies of Layer-2 rollups together with intelligent sharding have throughput, latency, and energy efficiency benefits without interfering with core security properties. Nevertheless, cross-shard communication, data availability, interoperability and a non-standardized cross-layer integration are some of the challenges that have been identified as areas of future research and collaboration with the industry.

VII. Conclusion

The survey contains a stringent and future-oriented overview of the research on blockchain scalability, finding Layer-2 scaling architecture and adaptive and AI-assisted sharding frameworks as the most feasible system architecture solutions to realize massively scalable decentralized systems. It discusses how by combining the findings of recent empirical assessments, architectural analysis and emerging standardization initiatives, the close bonding of Layer-2 schemes, especially rollups, and smart shard coordination could ensure throughput and latency shortcomings of monolithic blockchains, but leave the main security assurances intact. Transaction offloading and quick confirmation are facilitated by layer-2 techniques, and adaptive parallelism and reduction in cross-shard coordination costs are proposed by AI-driven sharding, which, together, provide significant improvements in performance, energy consumption, and sustainable performance over time without providing a reduction in decentralization. The survey also confirms that this hybrid paradigm is particularly useful with high-concurrent, latency-sensitive domains this will include IoT ecosystems, healthcare data exchange, intelligent transportation, and ridesharing platforms when real-time responsiveness and scalability are paramount. Lastly, it describes an explicit research path with a focus on strong cross-layer coordination, inter-shards communication security, adaptive resource management, and compliant with standards deployment, which makes this work a reference of high-quality and also a strategic roadmap to the design of next-generation, high-throughput, low-latency, and resilient blockchain infrastructures.

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