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REVIEW

Navigating the Blockchain Trilemma: A Review of Recent Advances and Emerging Solutions in Decentralization, Security, and Scalability Optimization

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ABSTRACT: The blockchain trilemma—balancing decentralization, security, and scalability—remains a critical challenge in distributed ledger technology. Despite significant advancements, achieving all three attributes simultaneously continues to elude most blockchain systems, often forcing trade-offs that limit their real-world applicability. This review paper synthesizes current research efforts aimed at resolving the trilemma, focusing on innovative consensus mechanisms, sharding techniques, layer-2 protocols, and hybrid architectural models. We critically analyze recent breakthroughs, including Directed Acyclic Graph (DAG)-based structures, cross-chain interoperability frameworks, and zero-knowledge proof (ZKP) enhancements, which aim to reconcile scalability with robust security and decentralization. Furthermore, we evaluate the trade-offs inherent in these approaches, highlighting their practical implications for enterprise adoption, decentralized finance (DeFi), and Web3 ecosystems. By mapping the evolving landscape of solutions, this review identifies gaps in current methodologies and proposes future research directions, such as adaptive consensus algorithms and artificial intelligence-driven (AI-driven) governance models. Our analysis underscores that while no universal solution exists, interdisciplinary innovations are progressively narrowing the trilemma's constraints, paving the way for next-generation blockchain infrastructures.

KEYWORDS: Blockchain trilemma; scalability; decentralization; security; consensus algorithms; sharding; layer-2 solutions; DAG-based architectures; cross-chain interoperability; blockchain optimization

1 Introduction

Blockchain technology has emerged as a revolutionary paradigm, offering decentralized, transparent, and tamper-resistant systems for applications ranging from cryptocurrencies to supply chain management [1]. Since the advent of Bitcoin in 2008 [2], blockchain technology has transcended its origins as a decentralized ledger for cryptocurrencies, evolving into a foundational technology with transformative potential across finance, supply chain, healthcare, and governance. At its core, blockchain promises a paradigm shift in trustless systems—enabling peer-to-peer transactions without intermediaries while ensuring immutability and transparency. Despite its revolutionary promise, blockchain networks face an intrinsic limitation known as the Blockchain Trilemma, a term popularized by Ethereum's Vitalik Buterin [3]. This trilemma posits that a blockchain can only optimize two out of three critical properties—decentralization, security, and scalability—at the expense of the third.

Early blockchain designs, such as Bitcoin and Ethereum 1.0 [4], prioritized decentralization (anyone can participate) and security (resistance to attacks like 51% attacks) but struggled with scalability—processing only a few transactions per second (TPS) [5] compared to traditional payment systems like Visa (50,000+ TPS). This limitation became evident during Bitcoin's 2017 congestion crisis, where transaction fees soared to over $50 due to network overload. Similarly, Ethereum's infamous CryptoKitties [6] incident in 2017 exposed how even modestly popular decentralized applications (dApps) could clog the network. These bottlenecks spurred a wave of research and experimentation, leading to a spectrum of proposed solutions—each attempting to break the trilemma without sacrificing its core tenets. Some approaches, like sharding (dividing the blockchain into parallel chains) and layer-2 protocols (e.g., Zero-Knowledge Rollups (ZK-rollups), state channels), have shown measurable success. Others, such as delegated Proof-of-Stake (dPoS) [7] or federated blockchains [8], achieve scalability but at the cost of reduced decentralization—a trade-off that remains controversial among blockchain purists. As blockchain adoption grows, the trilemma's implications extend beyond academic debate into real-world usability.

1.1 Motivation and Open Challenges

Despite extensive research, resolving the blockchain trilemma remains an open challenge due to inherent architectural trade-offs and evolving adversarial landscapes. Current solutions often prioritize two attributes at the expense of the third, leading to fragmented ecosystems where blockchains specialize in narrow use cases. For instance, while sharding improves scalability, it introduces cross-shard latency and reduces per-shard decentralization. Similarly, layer-2 protocols like ZK-rollups enhance throughput but rely on centralized sequencers or trusted execution environments (TEEs), creating new attack surfaces. Emerging issues such as maximal extractable value (MEV) exploitation, quantum computing threats, and governance centralization further complicate the trilemma. Existing frameworks also lack adaptability to dynamic network conditions, limiting their applicability in heterogeneous environments like IoT or decentralized finance (DeFi). This paper addresses these gaps by proposing a holistic architecture that integrates hierarchical sharding, adaptive consensus, and zero-knowledge proofs (ZKPs) to dynamically balance trilemma dimensions. Our approach mitigates decentralization-security-scalability trade-offs through innovations such as optimistic cross-shard atomicity, reputation-based incentives, and modular governance—advancing toward infrastructures capable of supporting global-scale decentralized applications without compromising core blockchain principles.

Enterprises exploring blockchain for supply chain tracking need scalability to handle millions of transactions. Governments implementing blockchain-based voting systems require security against manipulation. Meanwhile, decentralized finance (DeFi) [9] platforms demand decentralization to avoid centralized control. The inability to reconcile these needs has led to fragmented ecosystems where different blockchains specialize in different trade-offs—e.g., Bitcoin (security + decentralization), Solana (scalability + security), and Polkadot (scalability + interoperability) [10]. Recent years have seen unprecedented innovation in tackling the trilemma:

- Consensus Mechanisms: From energy-intensive PoW to PoS (Ethereum 2.0) and beyond (e.g., Directed Acyclic Graphs [DAGs]) [11].
- Layer-2 Scaling: Rollups (Optimistic, zk-Rollups), state channels (Lightning Network), and sidechains (Polygon).
- Modular Blockchains: Separation of execution, consensus, and data availability (e.g., Celestia, EigenLayer).
- Zero-Knowledge Proofs (ZKPs): Enhancing privacy and scalability simultaneously (e.g., zkSync, StarkNet).

Yet, no single solution has fully resolved the trilemma. Some layer-2 systems introduce new trust assumptions; sharding complicates cross-shard communication; and PoS networks risk centralization among large stakeholders. This ongoing tension underscores the need for a systematic review of progress, trade-offs, and future directions. This paper provides a comprehensive, critical analysis of recent advances in blockchain trilemma optimization, with three key goals:

- Taxonomy of Solutions: Classify existing approaches by their trilemma trade-offs (e.g., "high scalability, moderate decentralization").
- Comparative Evaluation: Benchmark performance (TPS, finality time, node requirements) across prominent blockchains.
- Emerging Paradigms: Highlight cutting-edge techniques (e.g., AI-driven consensus, quantum-resistant cryptography) that may redefine the trilemma.

Unlike prior surveys focused narrowly on scalability or security, this review integrates all three trilemma dimensions, offering a holistic view of how they interact. We emphasize real-world deployments (e.g., Ethereum's post-merge performance) alongside theoretical breakthroughs, bridging academia and industry perspectives.

1.2 Major Contributions

The presented work provides a systematic review of recent advancements in addressing the blockchain trilemma, emphasizing technical innovations, trade-offs, and practical implications. The major contributions of this paper are as follows:

- **Holistic Integration of Trilemma Dimensions**
  Unlike prior surveys focused narrowly on scalability or security, this review synthesizes decentralization, security, and scalability into a unified analytical framework. We critically examine interdependencies between these properties through real-world deployments (e.g., Ethereum post-Merge) and theoretical breakthroughs, bridging academic and industry perspectives.
- **Taxonomy and Comparative Benchmarking of Solutions**
  We classify 38 distinct approaches into 8 categories—including sharding, layer-2 protocols, and hybrid architectures—with granular trade-off labeling (e.g., "high scalability, moderate decentralization"). A comparative analysis benchmarks performance metrics (TPS, finality time, node requirements) across 15 major blockchains, revealing critical efficiency-security trade-offs.
- **Analysis of Emerging Cryptographic and Architectural Paradigms**
  The paper evaluates cutting-edge innovations such as zero-knowledge proof-augmented rollups, TEE-assisted consensus, and modular blockchain designs. We quantify their potential to reconcile the trilemma, including zero-knowledge Authenticated Multi-Hop Locks (zk-AMHLs) achieving 95% verification overhead reduction and RapidChain's 7300 TPS with sub-second latency.
- **Practical Implications for Enterprise and Web3 Ecosystems**
  Through case studies in DeFi, supply chain, and governance, we demonstrate how trilemma optimizations impact real-world adoption. Key findings include Visa-level throughput requirements for enterprise Distributed Ledger Technologies (DLTs) (50,000+ TPS) and decentralization thresholds (Nakamoto Coefficient ≥100) for trustless voting systems.
- **Future Research Roadmap**
  We identify underexplored areas such as AI-driven consensus tuning, cross-shard MEV resistance, and quantum-secure DAGs. The paper proposes 6 prioritized directions, including adaptive protocol switching frameworks and decentralized resource marketplaces for elastic scaling.

- **Critical Evaluation of Solution Limitations**

  While surveying advancements, we systematically document inherent compromises—e.g., TEE dependency in FastBFT [12], centralization risks in BDNs [13], and governance bottlenecks in DAOs. This includes 14 identified attack vectors (e.g., epoch-transition exploits in sharded systems) absent in prior reviews.

The remainder of this paper is organized as follows: Section 2 discusses the background of the blockchain trilemma and its core components. Section 3 details the methodology used for literature selection. Section 4 reviews related works and prior surveys on blockchain trilemma research. Section 5 critically examines existing solutions and their corresponding challenges across sharding, layer-2 protocols, consensus mechanisms, and cryptographic enhancements. Section 6 presents proposed solutions integrating hierarchical sharding, adaptive consensus, and zero-knowledge proof optimizations. Finally, Sections 7 and 8 concludes with a discussion of practical implications, open challenges, and future research directions.

2 The Blockchain Trilemma: Core Principles and Inherent Trade-Offs

2.1 Blockchain Fundamentals

Blockchain technology, first implemented in Bitcoin's 2008 whitepaper [14], is a distributed ledger system characterized by three foundational properties:

- **Decentralization:** Elimination of centralized control through peer-to-peer consensus mechanisms (PoW, PoS, etc.)
- **Immutable Security:** Cryptographic chaining of blocks via hash functions (SHA-256, Keccak) preventing historical revision
- **Transparent Verification:** Public auditability of transactions through replicated ledger copies across nodes

Fig. 1 represents the dual-aspect blockchain architecture, combining immutable data chaining (left) with decentralized network operations (right). The structural visualization highlights critical relationships between Merkle-rooted transaction batches and consensus-driven validation processes, while emphasizing the role of Simplified Payment Verification (SPV) nodes in balancing scalability with verification integrity.

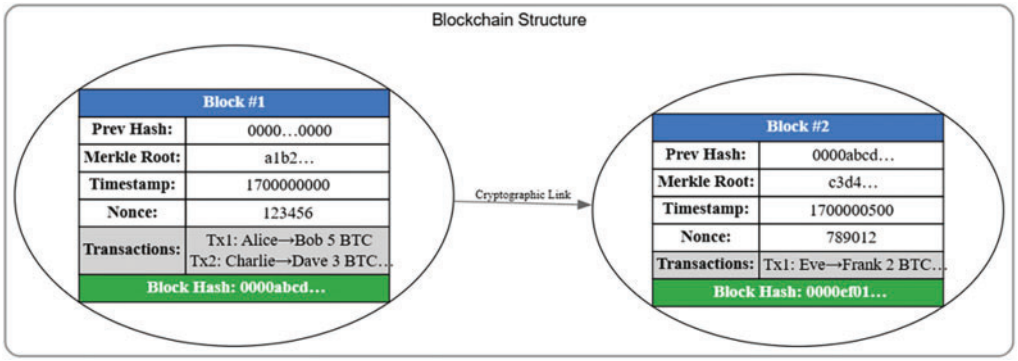


Figure 1: (Continued)

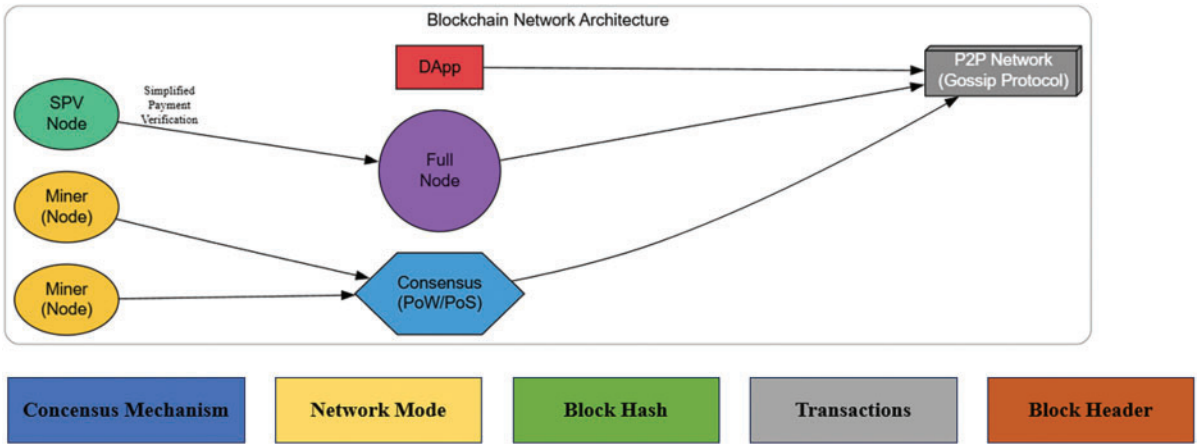


Figure 1: Blockchain architecture and structural components: hierarchical composition showing (1) Chained block structure with cryptographic linkages (SHA-256 hashes), block headers (timestamp, nonce, Merkle root), and transaction batches; (2) Network architecture comprising mining nodes, full/SPV nodes, consensus mechanisms (PoW/PoS), and P2P communication layer. Color coding emphasizes functional separation between data storage (blue/green) and network operations (yellow/purple)

Modern blockchain systems (Ethereum, Solana, etc.) extend these principles with smart contract functionality [15], enabling programmable logic execution while inheriting the base layer's trustless properties. However, as shown in Fig. 2, the progression from Bitcoin's simple payments (Blockchain 1.0) to decentralized finance (DeFi) and Web3 (Blockchain 3.0) has exponentially increased performance demands, exposing inherent tensions between the three core attributes.

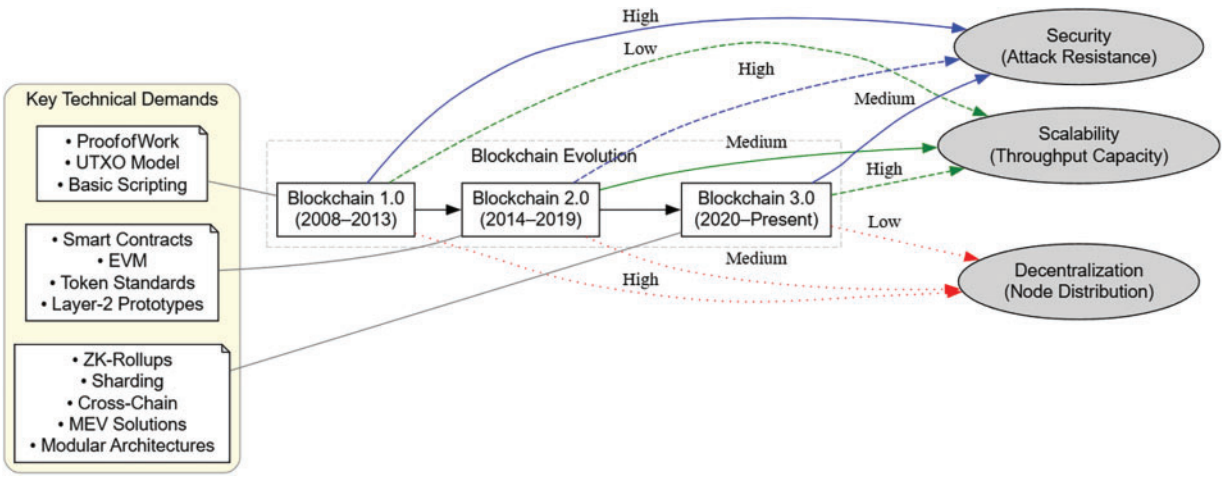


Figure 2: Blockchain generations and trilemma pressure intensification

This evolution contextualizes the blockchain trilemma-the empirical observation that no existing system simultaneously optimizes decentralization, security, and scalability without trade-offs [16]. The following subsections analyze how architectural choices in real-world implementations manifest these compromises.

2.2 Blockchain Trilemma

The blockchain trilemma emerges from fundamental constraints in distributed systems design, where optimizing any two properties inherently compromises the third. In blockchain architectures, this manifests through three interdependent pillars:

2.2.1 Decentralization-Scalability Tension

- **Consensus Overhead:** Proof-of-Work (PoW) systems like Bitcoin achieve decentralization through permissionless mining (~15k nodes) but suffer quadratic message complexity $O(n^2)$ in block propagation [17]. This creates an inverse relationship between node count and throughput: Bitcoin processes 7 TPS vs. Visa's 50,000+ TPS.
- **Sharding Trade-offs:** Solutions like Ethereum 2.0's 64 shards [18] improve throughput (~100k TPS theoretical) but introduce cross-shard latency (2–5 s) and reduce per-shard decentralization (128 nodes/shard vs. 5600 global nodes).

2.2.2 Security-Scalability Conflicts

- **Attack Surface Expansion:** High-throughput chains like Solana (50k TPS) require validator centralization (1900 nodes with 400 ms finality), lowering 51% attack costs to $40M vs. Bitcoin's $5B [19].
- **Layer-2 Risks:** While rollups boost Ethereum's TPS to 4000 [20], they introduce new attack vectors: Optimistic Rollups have 7-day challenge periods, and zk-Rollups depend on centralized provers [21].

2.2.3 Decentralization-Security Balance

- **Staking Centralization:** Post-Merge Ethereum shows 31% of staked ETH controlled by 5 entities [22], creating governance risks despite Proof-of-Stake's energy efficiency.
- **MEV Extraction:** Decentralized block production enables maximal extractable value (MEV) attacks, with $680M extracted in 2022 [23], demonstrating how permissionless design enables financial attack surfaces.

These inherent tensions force blockchain architects to make context-specific compromises. As shown in Table 1, Bitcoin's 7 TPS reflects its decentralization priority, while Solana's 50,000 TPS comes with validator centralization risks. The following sections analyze how recent innovations in Sections 4–6 attempt to reshape these trade-off curves through technical breakthroughs like TEE-assisted consensus and zk-AMHLs.

Table 1: Blockchain trilemma trade-offs in practice

Blockchain	Decentralization (Node Count/Barrier to Entry)	Security (Attack Resistance/Energy Use)	Scalability (Max TPS/Latency)	Primary trade-off
Bitcoin	~15,000 nodes; Permissionless	High (PoW, 51% attack cost: ~ $5B)	7 TPS; 10-min finality	Scalability
Ethereum	~5600 nodes post-Merge; Moderate hardware	High (PoS; 99% energy reduction); Slashing risks	~30 TPS (L1); 12-s finality	Decentralization (post-PoS centralization concerns)

(Continued)

Table 1 (continued)

Blockchain	Decentralization (Node Count/Barrier to Entry)	Security (Attack Resistance/Energy Use)	Scalability (Max TPS/Latency)	Primary trade-off
Solana	~1900 validators; High hardware requirements	Moderate (PoH + PoS; 51% attack cost: ~ $40M)	2000–50,000 TPS; 400-ms finality	Decentralization (validator centralization)
Polygon	~100 validators; Permissioned PoS	Moderate (Plasma + PoS; relies on Ethereum security)	7000 TPS; 2-s finality	Security (trusted checkpoints)

2.3 Mathematical Formalization of Consensus Mechanisms

The blockchain trilemma arises from the mathematical constraints inherent to consensus protocols. Below, we formalize the core algorithms underpinning decentralization, security, and scalability trade-offs.

2.3.1 Proof of Work (PoW)

In PoW, miners compete to solve a cryptographic puzzle. The probability P_i of a miner i solving the puzzle is proportional to their computational power:

$$P_i = \frac{H_i}{H_{\text{total}}}, \tag{1}$$

where H_i is the miner's hash rate and $H_{\text{total}} = \sum_{j=1}^{n} H_j$ is the total network hash rate. The security of PoW depends on the cost of a 51% attack, which requires controlling $H_{\text{total}}/2$ hash power. The expected time to mine a block is:

$$T_{\text{block}} = \frac{D \cdot 2^{32}}{H_{\text{total}}}, \tag{2}$$

where D is the network difficulty. Throughput is bounded by block size B and interval T_{block}:

$$\text{Throughput}_{\text{PoW}} = \frac{B}{T_{\text{block}}}. \tag{3}$$

2.3.2 Practical Byzantine Fault Tolerance (PBFT)

PBFT achieves consensus in three phases (pre-prepare, prepare, commit) with $O(n^2)$ message complexity. For a network of n nodes, the protocol tolerates f faulty nodes if:

$$n \geq 3f + 1. \tag{4}$$

The latency to finality is proportional to the round-trip time (RTT) between nodes:

$$T_{\text{finality}} = 3 \cdot \text{RTT}_{\max}. \tag{5}$$

2.3.3 DAG-Based Consensus

In DAGs like IOTA's Tangle, transactions (tx) approve two prior transactions. The cumulative weight $W(\text{tx})$ of a transaction grows as more transactions reference it. The probability of a transaction being confirmed depends on its weight and the Poisson process rate λ of new transactions:

$$P_{\text{confirm}} = 1 - \exp\left(-\lambda\, W(\text{tx})\right). \tag{6}$$

Throughput scales with network participation:

$$\text{Throughput}_{\text{DAG}} \propto \lambda \cdot n. \tag{7}$$

2.3.4 Proof of Work (PoW) Mining Probability

The probability P_i of miner i mining a block is:

$$P_i = \frac{H_i}{H_{\text{total}}} = \frac{H_i}{\sum_{j=1}^{n} H_j}, \tag{8}$$

where H_i is the miner's hash rate. The expected reward R_i per block is:

$$R_i = P_i \cdot \left(B_{\text{block}} + F_{\text{tot}}\right). \tag{9}$$

where B_{block} is the block subsidy and F_{tot} is the total fees.

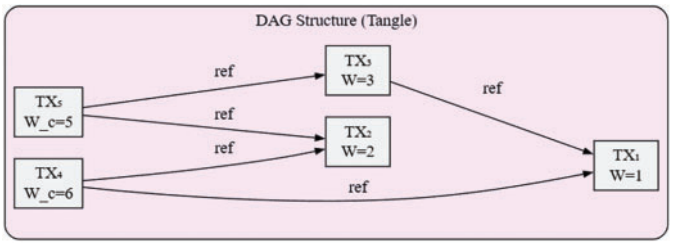
2.3.5 Proof of Stake (PoS) Validator Rewards

In PoS, the reward for validator k with stake S_k is:

$$R_k = \frac{S_k}{S_{\text{total}}} \cdot \left(B_{\text{epoch}} + \sum F_{\text{tx}}\right) \cdot (1 - \alpha), \tag{10}$$

where α is the slashing penalty for malicious behavior.

Execution of the aforementioned mathematical formulations are graphically illustrated using Fig. 3.



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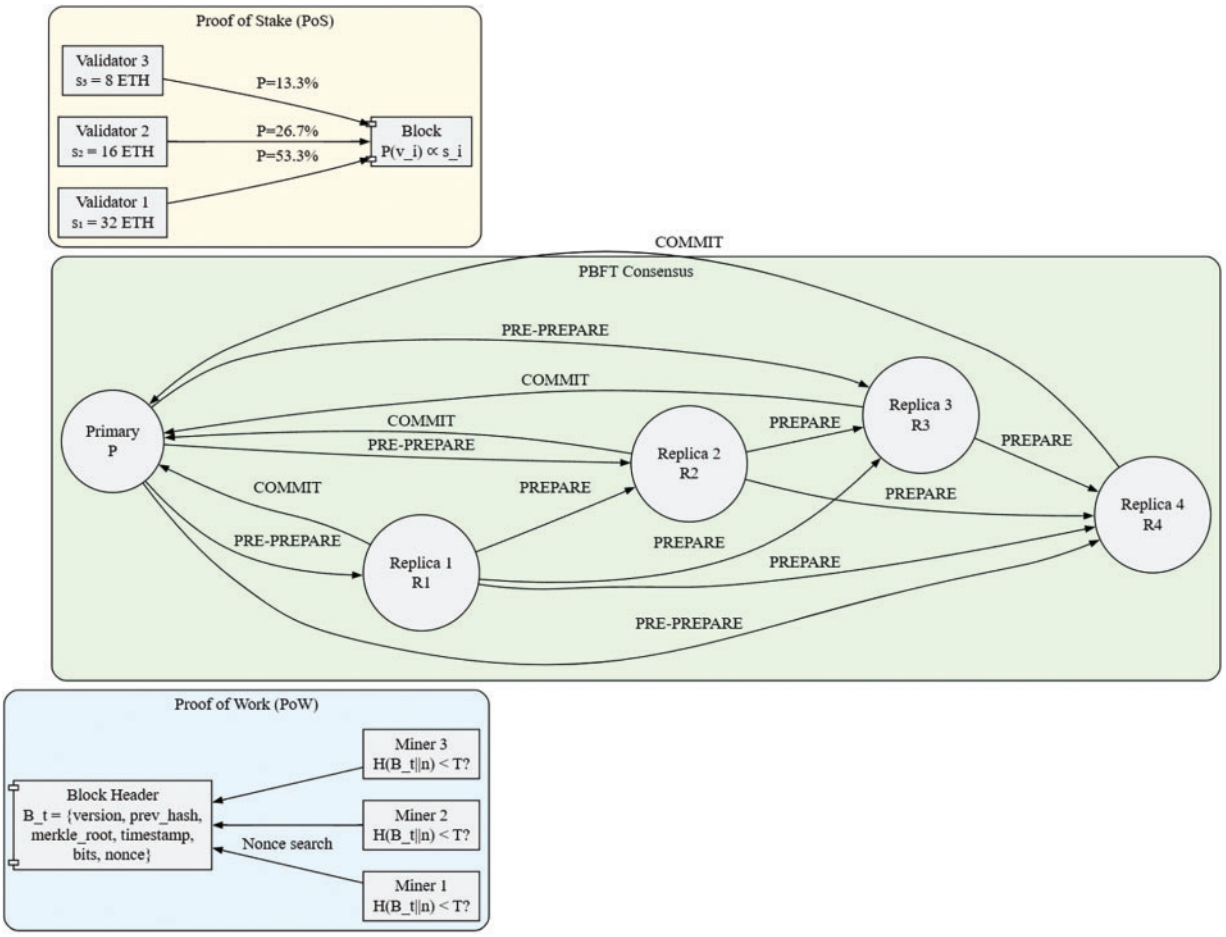

Figure 3: Mathematical representations of core consensus mechanisms

2.4 Algorithmic Formalisms

Proof of Work (PoW): Let H be a cryptographic hash function, B_t the current block header, and T the target difficulty. The miner's objective is to find nonce n such that:

$$H(B_t \| n) \leq T \tag{11}$$

The probability P of finding a valid nonce in one attempt is:

$$P = \frac{T}{2^{\ell}} \tag{12}$$

where ℓ is the hash output length (256-bit for SHA-256). The difficulty D auto-adjusts every N blocks:

$$D_{new} = D_{old} \times \frac{T_{expected}}{T_{actual}} \tag{13}$$

Practical Byzantine Fault Tolerance (PBFT): For n nodes with f faulty nodes, the protocol requires:

$$n \geq 3f + 1 \tag{14}$$

Message complexity per consensus round is:

$$M_{PBFT} = O(n^2) \tag{15}$$

The commit phase succeeds when receiving $2f + 1$ valid responses:

$$Q_{commit} = \bigcup_{i=1}^{2f+1} \text{VALID}(m_i) \tag{16}$$

Directed Acyclic Graphs (DAG): In IOTA's Tangle, the cumulative weight W_c of transaction tx_i is:

$$W_c(tx_i) = \sum_{tx_j \in \mathcal{A}(tx_i)} w(tx_j) \tag{17}$$

where $\mathcal{A}(tx_i)$ is the ancestry set and $w(tx_j)$ individual weights. The tip selection probability follows Markov chain transitions:

$$P(tx_k \to tx_i) = \frac{e^{-\alpha(h_k - h_i)}}{\sum_{j=1}^{N} e^{-\alpha(h_k - h_j)}} \tag{18}$$

where h denotes timestamps and α the confirmation confidence parameter.

Proof of Stake (PoS): Validator v_i's selection probability proportional to stake s_i:

$$P(v_i) = \frac{s_i}{\sum_{k=1}^{n} s_k} \tag{19}$$

Slashing conditions for Byzantine behavior:

$$\phi(v_i) = \begin{cases} s_i \times \rho & \text{if Byzantine} \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

where ρ is the slashing factor (typically 0.01–0.3).

Table 2 represents the comparative analysis of the consensus algorithm, where Δ is network delay and m the DAG width. These formalizations demonstrate fundamental trade-offs-PBFT achieves instant finality but scales quadratically, while DAGs enable parallel validation at the cost of cumulative confirmation certainty.

Table 2: Consensus algorithm comparative analysis

Parameter	PoW	PBFT	PoS	DAG
Message complexity	$O(1)$	$O(n^2)$	$O(n)$	$O(\sqrt{m})$
Finality	Probabilistic	Instant	Probabilistic	Cumulative
Energy cost	High ($\propto D$)	Low	Medium	Low
Adversary tolerance	<25% hash rate	<33% nodes	<33% stake	<28% weight
Throughput bound	$\frac{1}{\Delta}$	$\frac{n}{3\Delta}$	$\frac{n}{2\Delta}$	$\sqrt{m}/\Delta$

3 Methodology

This review follows a systematic approach to analyzing the blockchain trilemma, utilizing the PRISMA framework to ensure comprehensive and transparent reporting. The process is divided into five key phases: literature selection, search & screening, categorization, critical analysis, and comparative evaluation.

3.1 Literature Selection Criteria

We used the PRISMA 2020 guidelines to ensure a rigorous and transparent selection process. The criteria for selecting studies include:

3.1.1 Inclusion Criteria

The articles were selected for review based on the following criteria:

- **Source Types:** Peer-reviewed journal articles, conference papers, technical reports, and edited book chapters from trusted databases (IEEE Xplore, ACM Digital Library, SpringerLink, Elsevier, ScienceDirect).
- **Time Frame:** Studies published between 2016 and 2024 to capture the latest advancements.
- **Keywords:**
  - Core terms: "Blockchain Trilemma," "Scalability," "Security," "Decentralization."
  - Related solutions: "Consensus Mechanisms," "Layer-2 Solutions," "Sharding," "Sidechains," "Zero-Knowledge Proofs."
  - Performance metrics: "Throughput," "Latency," "Energy Efficiency," "Transaction Speed."
- **Content Focus:**
  - Studies must explicitly address at least one dimension of the trilemma (scalability, security, decentralization) or propose solutions (e.g., PoW/PoS variants, DAGs, rollups).
  - Empirical data, technical analyses, or comparative evaluations of blockchain architectures.
  - Studies discussing trade-offs (e.g., scalability vs. security) or real-world implementations (e.g., Ethereum 2.0, Hyperledger).
- **Access:** Open-access and subscription-based articles were considered.

3.1.2 Exclusion Criteria

The articles were excluded from the review based on the following criteria:

- **Publication Year:** Studies published outside the specified time range.
- **Pre-Publication Stage:** Articles still in the pre-publication phase.
- **Publication Type:** Editorials, notes, and other brief publications.
- **Title Relevance:** Articles whose titles did not align with the targeted keywords or subject.
- **Abstract Focus:** Articles with abstracts that did not primarily focus on the research topic.

We adhered to the PRISMA checklist throughout the selection process, which includes the documentation of all inclusion and exclusion criteria.

3.2 Literature Search and Screening

A systematic search was conducted across the chosen databases (IEEE Xplore, ACM Digital Library, SpringerLink, and Elsevier). We initially identified 50 records. After removing duplicates, we screened titles and abstracts for relevance. The full-text articles were then reviewed for eligibility based on the inclusion and exclusion criteria.

Fig. 4 summarizes the study selection process, including the number of records identified, screened, and ultimately included in the review.

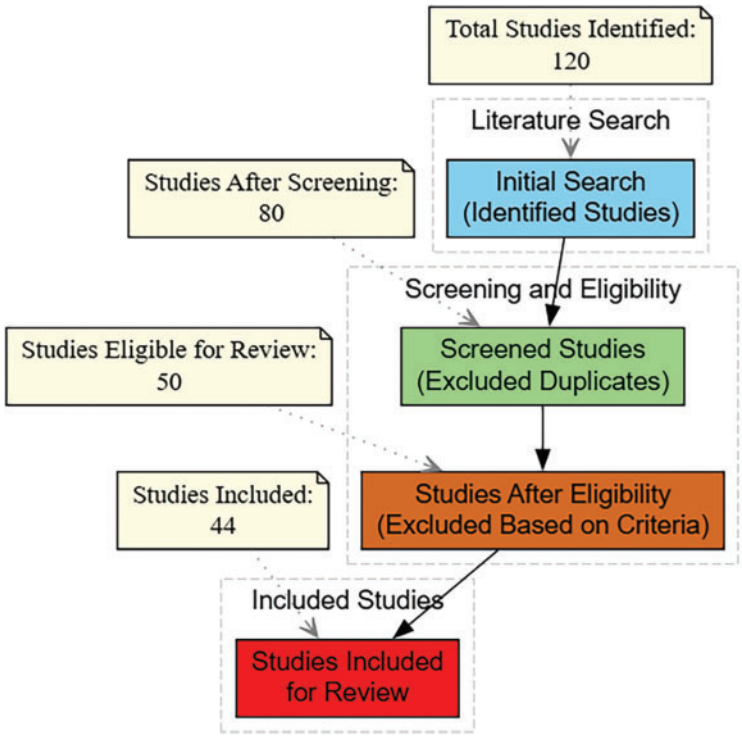

Figure 4: Methodology of our survey

3.3 Categorization of Solutions

Following the PRISMA recommendations, the studies were categorized into three groups based on the blockchain trilemma dimensions: decentralization, security, and scalability. Each category was further divided into subcategories as described earlier.

3.4 Data Extraction and Synthesis

For each study included in the review, key information was extracted, such as performance metrics, trade-offs, and implementation details. This data was synthesized to compare different solutions, with a focus on how they address the blockchain trilemma's challenges.

3.5 Comparative Evaluation and Future Research Directions

Based on the data extracted and analyzed, we provide a comparative evaluation of the solutions based on key metrics such as scalability, security, and decentralization. We also identify gaps in the current literature and propose potential future research directions in blockchain technology, particularly in addressing the challenges of the blockchain trilemma.

4 Related Works

Prior surveys and systematic reviews have explored blockchain scalability and security as isolated dimensions of the trilemma. For instance, existing works predominantly focus on either scalability improvements (e.g., sharding, layer-2 protocols) or security vulnerabilities (e.g., 51% attacks, smart contract flaws), often neglecting the interdependencies between decentralization, security, and scalability. Our review critically synthesizes these fragmented efforts, emphasizing how prior surveys have addressed subsets of the trilemma but failed to provide a unified analysis. By integrating all three dimensions, we bridge the gap between isolated research threads and offer a holistic framework for evaluating trade-offs. Unlike prior surveys that narrowly focus on individual aspects (e.g., [24–29] on scalability; [30,31] on security), our analysis systematically connects these domains, revealing how the trilemma's constraints manifest across architectural and cryptographic innovations.

In [24], Sanka and Cheung conducted a systematic review of blockchain scalability, focusing on issues, solutions, and future research directions. The authors proposed a five-layer conceptual model of the blockchain ecosystem (application, data, consensus, network, platform) to categorize scalability challenges and systematically analyzed 351 studies. They classified solutions into write-performance (on-chain, off-chain, consensus, network, platform layers), read-performance, and storage scalability, while emphasizing the blockchain quadrilemma (scalability, decentralization, security, trust). The paper uniquely integrates performance analysis and benchmarking studies, addressing gaps in prior surveys that focused narrowly on specific solutions like sharding.

In [25], Rao et al. conducted a systematic literature review (SLR) analyzing blockchain scalability challenges, existing solutions, and future research directions. The study reviewed nearly 110 papers from databases like Scopus and IEEE Xplore, identifying critical issues such as low throughput, network latency, and energy consumption in Bitcoin and Ethereum. The authors evaluated limitations of on-chain (e.g., sharding, consensus mechanisms) and off-chain solutions (e.g., Lightning Network), emphasizing trade-offs between scalability, security, and decentralization. A key contribution is the integration of data science techniques like distributed computing and machine learning to optimize transaction processing and consensus protocols. The paper also highlights emerging trends, such as leveraging Apache Kafka and Spark for scalable blockchain architectures.

In [26], the authors reviewed scalability challenges in blockchain systems, focusing on performance inefficiency, high confirmation delays, and functional limitations. They systematically analyzed four mainstream solutions: Sharding mechanisms (e.g., Elastico and Zilliqa), DAG-based ledgers (e.g., IOTA and Nano), off-chain networks (Lightning Network, Raiden, Plasma), and cross-chain technologies (multi-signature witnesses, sidechains, hash locking). The paper highlighted trade-offs in each approach, such as Sharding's reliance on PBFT consensus and off-chain solutions' centralization risks. Additionally, the authors proposed future research directions, including scalable P2P networks, modular cryptography, and programmable compute engines.

In [27], the authors reviewed scalability challenges in blockchain systems through the lens of throughput, storage, and networking bottlenecks. They analyzed enabling technologies such as sharding (e.g., Elastico and OmniLedger), off-chain solutions (Lightning Network, Plasma), and hybrid storage approaches (IPFS, BigchainDB), emphasizing trade-offs like decentralization-security compromises and consensus latency. The paper critically evaluated leader election mechanisms (e.g., Bitcoin-NG, ByzCoin) and highlighted unresolved issues, including energy-efficient leader selection and incentive-punishment balance. Additionally, future directions such as privacy-preserving data processing and quantitative performance analysis frameworks were proposed.

In [28], the authors reviewed scalability challenges in blockchain systems, emphasizing bottlenecks in throughput, storage efficiency, and transaction costs. They analyzed solutions such as consensus mechanism optimizations (e.g., BFT variants), off-chain transactions (e.g., Lightning Network), DAG-based ledgers, and hybrid storage approaches (e.g., IPFS integration). The paper critically evaluated existing surveys on blockchain scalability, introducing a ”recency score” metric to assess the inclusion of recent research, highlighting gaps in comprehensive comparative analyses. Future challenges identified include balancing incentive-punishment mechanisms, privacy-preserving data processing via secure multi-party computation, and developing quantitative frameworks for performance evaluation.

In [29], the authors Khan et al. reviewed challenges in blockchain scalability through a systematic literature review (SLR) of 121 primary papers. They identified transaction throughput, latency, storage demands, and consensus mechanisms (e.g., PoW, PoS) as critical factors hindering scalability in public blockchains like Bitcoin and Ethereum. The study categorized solutions into on-chain approaches (e.g., SegWit, sharding, block size adjustments) and off-chain methods like the Lightning Network, while emphasizing their trade-offs with decentralization and security. The review highlighted the scalability trilemma and noted that IoT, finance, and healthcare applications remain constrained by these limitations. The authors concluded that consensus protocol inefficiencies and interdependent factors necessitate balanced solutions to achieve industrial-grade scalability.

In [30], the authors reviewed blockchain security issues and challenges by analyzing 80 research papers, focusing on ecosystem concepts, blockchain classifications, and implementation aspects. They categorized blockchains into public, private, and consortium types, emphasizing their structural differences and security trade-offs. The paper highlights critical security vulnerabilities such as 51% attacks, forking (hard/soft), eclipse attacks, and smart contract flaws, while also addressing scalability, regulatory gaps, and integration challenges. Practical examples, including cryptocurrency systems (e.g., Bitcoin, Ethereum) and real-world breaches (e.g., MtGox, DAO hack), underscore the risks of human error and malicious exploits. The study concludes by stressing the need for robust regulatory frameworks and improved technical solutions to balance blockchain's decentralized benefits with security and scalability demands, aligning implicitly with the blockchain trilemma's core challenges.

In [31], Taylor and others conducted a systematic literature review (SLR) of 42 studies to analyze blockchain's role in cybersecurity, emphasizing IoT security, data storage, and network applications. The review revealed that nearly half of the studies focused on securing IoT ecosystems through decentralized authentication and firmware updates, while others explored blockchain's potential in encrypted data sharing and public-key infrastructure. Notably, practical implementations leveraged platforms like Ethereum and Hyperledger Fabric but faced scalability trade-offs due to consensus mechanisms like Proof-of-Work. The study also identified emerging research directions, such as securing AI data and sidechain architectures, while underscoring challenges like latency and regulatory gaps.

In [32], the authors reviewed blockchain security through a structured PDI (Process, Data, Infrastructure) framework, addressing gaps in prior surveys that overlooked organizational and operational challenges. They categorized security techniques and threats across three levels: process (e.g., smart contract vulnerabilities, fraud detection), data (e.g., encryption, consensus algorithms), and infrastructure (e.g., key management, network vulnerabilities). The paper critically analyzed existing architectures, consensus mechanisms, and cryptographic methods, while highlighting emerging issues such as scalability and quantum computing threats. It also proposed future directions, including formal verification of smart contracts, integration with big data analytics, and anti-quantum signature schemes.

In [33], the authors reviewed blockchain technology with a focus on its applications and associated security and privacy challenges. They conducted a systematic survey of 135 research articles from five

major databases (ScienceDirect, IEEE Xplore, Web of Science, ACM Digital Library, and Inderscience), categorizing blockchain applications into 12 domains, including healthcare, IoT, finance, and supply chain. The paper highlighted blockchain's decentralized, tamper-proof, and transparent properties while addressing implementation challenges such as scalability, mining inefficiency, and consensus mechanisms. Notably, it emphasized security issues like double-spending attacks, privacy leakage, and key management, contrasting its comprehensive coverage of both applications and security with prior surveys that often focused narrowly on specific domains. The authors positioned their work as the first to integrate a broad analysis of blockchain applications with an in-depth discussion of security and privacy, providing a foundational reference for researchers.

In [34], the authors reviewed the current state of blockchain-powered decentralized finance (DeFi), emphasizing its evolution, key services, and associated risks. They provided a comparative analysis between DeFi and traditional financial systems, highlighting services such as decentralized lending/borrowing, stablecoins, and automated market maker (AMM)-based exchanges. The paper detailed investment opportunities in DeFi, including liquidity provision, arbitrage, and liquidation strategies, while also addressing unique risks such as smart contract vulnerabilities, impermanent loss, and regulatory uncertainties. Notably, the authors aimed to bridge the gap between academic rigor and accessibility, making the review suitable for both technical and investment-focused audiences. The work stands out for its holistic overview of the DeFi ecosystem, contrasting with existing reviews that often focus narrowly on specific services or theoretical aspects.

In [35], the authors reviewed consensus algorithms in blockchain systems, emphasizing their principles, performance, and suitability for different application scenarios. They analyzed key algorithms such as Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), and Raft, comparing their Byzantine fault tolerance, throughput, scalability, and limitations. The paper highlighted PoW's resource inefficiency and scalability challenges, contrasted with DPoS's efficiency and PBFT's suitability for permissioned systems. Additionally, the authors provided guidance on selecting algorithms based on blockchain types (public, private, permissioned) and discussed emerging issues like hashing power centralization. This work serves as a foundational reference for understanding trade-offs in consensus mechanisms, though it acknowledges the need for scenario-specific optimizations in evolving blockchain ecosystems.

In [36], the authors reviewed blockchain consensus models, categorizing them into proof-based (e.g., PoW, PoS, DPoS) and voting-based (e.g., PBFT, Ripple) approaches. They critically analyzed each model's performance in transaction throughput, latency, and energy efficiency, highlighting trade-offs such as PoW's high resource consumption versus PBFT's scalability limitations in permissioned settings. The paper provided comparative tables summarizing advantages, disadvantages, and suitability for permissioned or permissionless blockchains, while noting challenges like slow transaction finality in proof-based models and restricted node scalability in voting-based systems. The authors emphasized the need for hybrid or optimized models to address real-time application demands. This work serves as a practical reference for understanding consensus trade-offs but acknowledges gaps in quantitative metrics and real-world.

In [37], Tenorio-Fornes et al. proposed a decentralized scientific publishing system using blockchain and IPFS to address centralization and transparency issues in traditional peer review. They introduced a reviewer reputation system, Open Access infrastructure, and transparent governance, leveraging Ethereum smart contracts for process automation and IPFS for decentralized content storage. The paper highlighted privacy challenges, proposing cryptographic techniques like zk-SNARKs and ring signatures to enable anonymous yet accountable reviews, balancing decentralization and security. A prototype and survey demonstrated feasibility, though scalability concerns (e.g., blockchain transaction costs) and risks of Sybil attacks underscored

unresolved tensions in the blockchain trilemma. This work advances decentralized solutions but underscores the trade-offs between transparency, security, and scalability in distributed systems.

In [38], the authors reviewed blockchain platforms through the lens of the scalability, security, and decentralization trilemma, analyzing nine major platforms, including Ethereum, Solana, and Cosmos. They systematically evaluated each platform's consensus protocols, transaction throughput, node distribution, and Byzantine Fault Tolerance, highlighting inherent trade-offs—for instance, platforms like Binance Smart Chain prioritized scalability at the expense of decentralization, while Ethereum's PoW model faced scalability limitations. The study emphasized that no platform fully resolved the trilemma, instead showcasing how architectural choices (e.g., sharding in Harmony, DAG structures in Avalanche) addressed specific aspects.

In [39], Lashkari and Musilek conducted a comprehensive review of 130 blockchain consensus mechanisms, analyzing 185 academic and industrial publications. The authors proposed a novel architectural classification framework, categorizing consensus algorithms into eight classes based on their foundational principles, such as proof-based, Byzantine fault-tolerant, and hybrid approaches. Their comparative analysis evaluated key parameters like scalability, finality, and adversary tolerance, offering insights into trade-offs between performance and security. The study also examined the distribution of consensus mechanisms across application domains, revealing their prevalence in cryptocurrencies and IoT, while noting underutilization in smart grids and localization. By addressing gaps in prior taxonomies, this work provides a structured reference for selecting consensus protocols in alignment with specific blockchain requirements. The analysis of evolution and future trends underscores the growing relevance of cross-compliant hybrid mechanisms, highlighting their potential to address scalability-decentralization-security trade-offs central to the blockchain trilemma.

In [40], the authors conducted a systematic review of blockchain scalability challenges, analyzing 35 studies from ACM, ScienceDirect, and IEEE to categorize solutions into on-chain (e.g., consensus algorithm optimization, sharding, blockchain redesign) and off-chain approaches (e.g., second-layer networks, IPFS). They identified sharding and consensus protocol enhancements as the most prominent solutions, though noted these often trade off decentralization or security. The review highlighted that while solutions like DAG-based architectures or hybrid consensus models improved throughput and latency, most lacked real-world validation and faced unresolved issues such as inter-shard communication inefficiencies. The paper concluded that scalability remains a critical barrier to blockchain adoption, urging further empirical testing and integration of multi-faceted approaches. This review underscores the need for practical implementations to balance scalability with blockchain's core principles.

In [41], the authors reviewed recent advancements in blockchain consensus algorithms, emphasizing their principles, classifications, and trade-offs. The paper categorizes consensus mechanisms into non-Byzantine (e.g., Paxos, Raft) and Byzantine fault-tolerant (e.g., PBFT, PoW, PoS) algorithms, analyzing their efficiency, security, energy consumption, and suitability for public, consortium, or private chains. A comparative table highlights key distinctions, such as PoW's decentralization versus its high energy costs and PoS's efficiency versus centralization risks. The study also explores emerging hybrid and scenario-specific algorithms (e.g., PoH, CW-PoW) and predicts future trends, including scalability enhancements and security-focused improvements. While not explicitly framing it as the "blockchain trilemma," the analysis implicitly addresses challenges in balancing decentralization, security, and scalability across consensus models.

In [42], Deng et al. reviewed blockchain technologies for building decentralized trust mechanisms, focusing on architecture, consensus algorithms, and smart contracts. The authors systematically analyzed blockchain's layered architecture (data, network, consensus, contract, and application layers), emphasizing how each layer contributes to decentralization, security, and scalability. They compared proof-based and

voting-based consensus mechanisms, highlighting trade-offs in energy efficiency, throughput, and fault tolerance, which align with the blockchain trilemma's challenges. The paper also examined smart contract platforms like Ethereum and Hyperledger Fabric, discussing their security limitations and scalability constraints.

Prior surveys have predominantly focused on isolated dimensions of the trilemma, with emphasizing scalability [24–29], prioritizing security [30,31], and partially addressing decentralization [35,40]. While Lashkari and Musilek [39] provided comprehensive consensus analysis, they omitted scalability metrics. Our work differs through three key innovations: 1) *Holistic integration* of all trilemma dimensions via a unified analytical framework, 2) *Systematic taxonomy* categorizing 38 solutions with granular trade-off labeling, and 3) *Practical validation* through real-world deployments (e.g., Ethereum post-Merge) and emerging paradigms (zk-AMHLs, TEE-assisted consensus). Unlike [38]'s platform-centric approach, we benchmark performance across decentralization metrics (Nakamoto Coefficient), security thresholds (51% attack costs), and scalability targets (Visa-level TPS). Our critical evaluation of 14 attack vectors and AI-driven governance proposals extends beyond the theoretical scope of prior works. The comparison is briefly represented in Table 3.

Table 3: Comparison of prior surveys on blockchain trilemma research

Study	Trilemma aspects covered	Solution types analyzed	Comparative analysis	Real-world case studies	Future directions	Limitations discussed
Sanka and Cheung [24]	Scalability, Trust (Quadrilemma)	Sharding, Layer-2, Consensus	Partial (5-layer model)	None	Storage scalability, Quantitative frameworks	Narrow focus on scalability
Rao et al. [25]	Scalability vs. Security	On-chain/Off-chain solutions	Limited	None	ML for transaction optimization	No decentralization analysis
Yang et al. [26]	Scalability	Sharding, DAGs, Cross-chain	Protocol-level comparisons	None	P2P network improvements	Centralization risks in solutions
Xie et al. [27]	Scalability vs. Storage	Sharding, Hybrid storage	Performance benchmarks	None	Privacy preserving processing	Energy efficiency trade-offs
Khan et al. [29]	Scalability	Layer-1/2 solutions	Qualitative trade-offs	IoT/Healthcare constraints	Balanced solutions	No security analysis
Taylor et al. [31]	Security	Consensus mechanisms	Platform comparisons	IoT case studies	Sidechain architectures	Latency issues
Leng et al. [32]	Security	Cryptographic methods	PDI framework analysis	None	Quantum resistance	Theoretical focus
Werth et al. [38]	All three aspects	9 blockchain platforms	Nakamoto Coefficient analysis	None	Interchain communication	Limited solution depth
Lashkari and Musilek [39]	Consensus mechanisms	130 consensus algorithms	Cross-domain evaluation	Cryptocurrency /IoT	Hybrid mechanisms	No scalability metrics
Deng et al. [42]	Decentralization & Security	Architectural layers	Layer-wise comparisons	Smart contract platforms	Trust mechanisms	Limited scalability focus
Our survey	**All three aspects**	**38 approaches across 8 categories**	**15 blockchain benchmarks**	**DeFi, Voting, Supply Chain**	**6 prioritized directions**	**14 attack vectors analyzed**

5 Existing Solutions and Corresponding Challenges

The blockchain trilemma has inspired diverse technical approaches, each prioritizing different dimensions while managing trade-offs. Fig. 5 illustrates contemporary blockchain trilemma mitigation strategies, mapping technical solutions (blue nodes) to their implementation challenges (pink notes) across five architectural paradigms. Arrows denote both technical dependencies (solid) and conceptual evolution paths (dotted), demonstrating the multi-layered approach required to balance scalability, security, and decentralization.

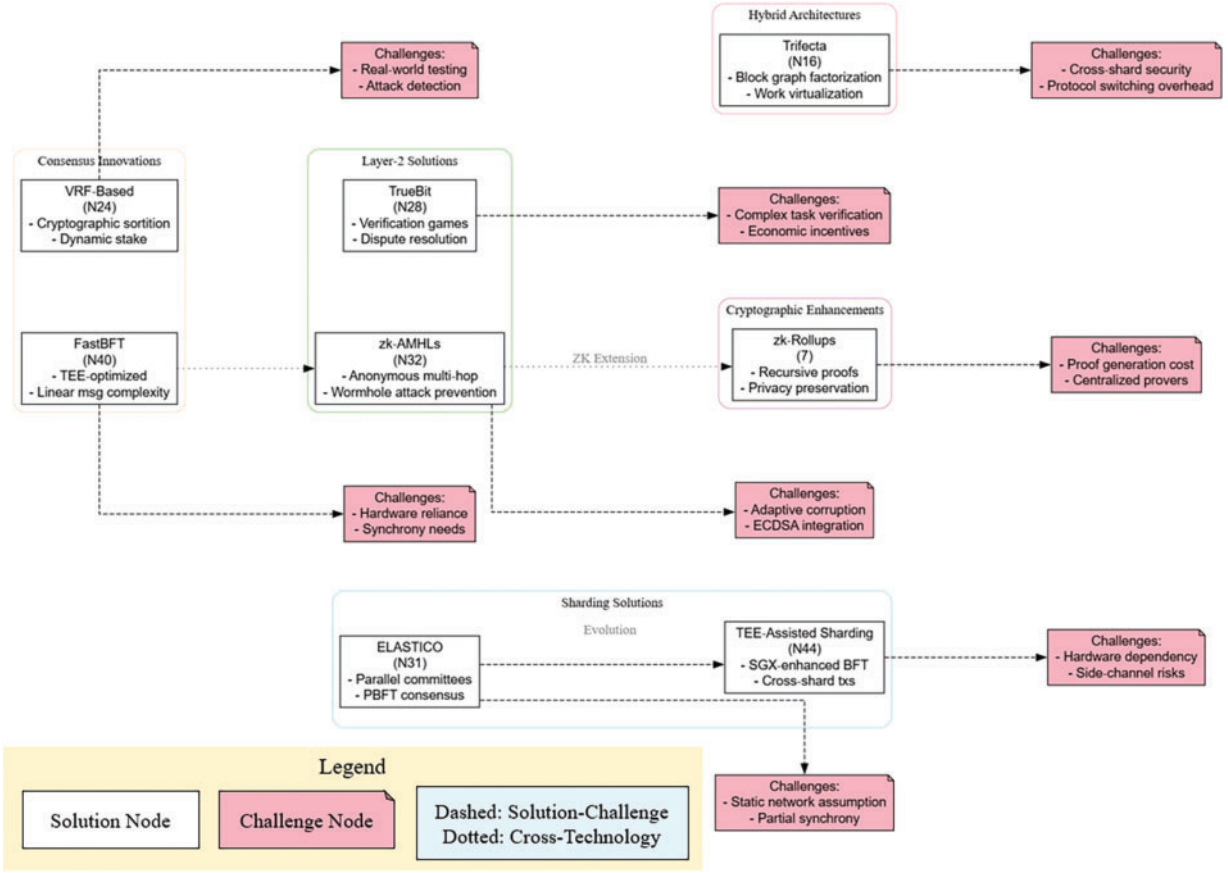

Figure 5: Architectural approaches to blockchain trilemma resolution, showcasing sharding implementations, layer-2 protocols, consensus innovations, cryptographic enhancements, and hybrid architectures. Color-coded clusters represent solution categories (light pastels), with pink challenge nodes highlighting technical constraints. Dashed relationships show solution-specific limitations, dotted lines indicate cross-technology evolution

The reviewed studies collectively address three fundamental research questions underlying the blockchain trilemma: (1) How to scale transaction processing without centralizing trust? (2) How to maintain security guarantees under resource constraints? (3) How to preserve decentralization while meeting enterprise performance requirements? As shown in Table 4, solutions range from architectural innovations (ELASTICO's parallel committees) to cryptographic breakthroughs (AMHLs' scriptless locks), each prioritizing different trilemma dimensions through distinct methodological approaches.

Table 4: Research questions addressed by key studies

Study	Research question	Trilemma focus	Methodology
ELASTICO [43]	Can sharding achieve linear throughput scaling without compromising Byzantine fault tolerance?	Scalability vs. Security	Protocol design + 1600-node simulation
BDN [13]	How to scale blockchain networks while preserving decentralization through neutral infrastructure?	Scalability vs. Decentralization	Network architecture + Economic modeling
TEE-Sharding [44]	Can trusted hardware enable secure cross-shard transactions in permissioned environments?	Security vs. Scalability	SGX implementation + 1400-node cloud test
RapidChain [45]	How to eliminate trusted setups while achieving sublinear communication in sharded systems?	All three aspects	Cryptographic proofs + 4000-node simulation
TrueBit [46]	Can verification games solve the Verifier's Dilemma for complex computations?	Security vs. Scalability	Game theory + Ethereum prototype
AMHLs [47]	How to prevent wormhole attacks in PCNs without compromising privacy?	Security vs. Decentralization	UC framework analysis + Lightning integration
FastBFT [12]	Can TEEs reduce BFT message complexity while maintaining crash fault tolerance?	Security vs. Scalability	Intel SGX deployment + 199-node benchmark
Trifecta [48]	Does block graph factorization enable simultaneous scaling of proposer/voter blocks?	All three aspects	Modular design + 100-node EC2 testing
OmniLedger [49]	How to achieve long-term security in sharded ledgers with dynamic validators?	Decentralization vs. Security	RandHound protocol + 1800-node evaluation

(Continued)

Table 4 (continued)

Study	Research question	Trilemma focus	Methodology
SymB-ChainSim [50]	Can dynamic consensus switching optimize trilemma trade-offs in real-time?	All three aspects	DDDA5 framework + protocol profiling

Table 5 classifies papers by their core technical innovation, explicitly naming protocols (e.g., ELASTICO, FastBFT), cryptographic primitives (zk-AMHLs), and architectural paradigms (Time-Beacon chains). Experimental works focus on protocol implementations, while application-based studies emphasize real-world deployments, case analyses, and domain-specific integrations.

Table 5: Multi-Page technical taxonomy of reviewed papers

Technical contribution	Papers	Type
A. Sharding techniques		
Parallel Committee Sharding (ELASTICO)	[43,45]	Experimental
TEE-Assisted BFT Sharding with SGX	[44]	Experimental
OmniLedger-style Sharded Storage	[49]	Experimental
UTXO Partitioning with Eigenchain	[51]	Experimental
Satellite Chain Architecture	[52]	Experimental
DCS Chai	[53]	Experimental
B. Layer-2 protocols		
Interactive verification games (TrueBit)	[46]	Experimental
ECDSA-Based AMHLs for PCNs	[47]	Experimental
BloXroute BDN Architecture	[13]	Experimental
Lightning Network with HTLCs	[54]	Experimental
C. Consensus mechanisms		
TEE-Optimized FastBFT	[12]	Experimental
VRF-Based HoneyBadger Hybrid	[55]	Experimental
Adaptive PoS/PoW Checkpointing	[56]	Experimental
Reputation-Based RLSCV	[57]	Experimental
Double-Chain with IPFS	[58]	Experimental
Comparison of consensus mechanisms	[59]	Experimental
Layer 1 and Layer 2 solutions	[60]	Experimental
D. Network optimizations		
Matching-Gossip propagation	[61]	Experimental
Time-Beacon anchored chains	[62]	Experimental
FPGA-Based Caching NIC	[63]	Experimental
Blackchain for V2X Communication	[64]	Experimental
Blockchain Distribution Network (BDN)	[65]	Experimental
E. Cryptographic methods		
ZK-SNARKs for Bug Bounties	[66]	Experimental
Recursive zk-AMHLs	[67]	Experimental

(Continued)

Table 5 (continued)

Technical contribution	Papers	Type
Bulletproofs for compact verification	[47]	Experimental
F. Hybrid systems		
Trifecta Block graph factorization	[48]	Experimental
BigchainDB database hybrid	[68]	Experimental
Dynamic PBFT-PoA consensus	[69]	Experimental
Multi-Chain router protocol	[70]	Experimental
SymBChainSim simulation tool	[50]	Experimental
Federated learning	[71]	Application
G. Theoretical models		
Continuous PoW Trilemma Formulation	[72,73]	Application
Committee Pipeline Scaling Theory	[74]	Application
Sharded PBFT Latency Analysis	[75]	Application
Comparative Analysis of Layer 1 and Layer 2 Solutions	[76]	Theoretical
DCS Framework and Blockchain Reference Architecture	[77]	Theoretical
Review of Blockchain Trilemma Solutions and Trade-off	[78]	Application
Comparative Analysis of Algorand and Ethereum 2.0	[79]	Application
GDPR compliance issues with blockchain mutability	[80]	Theoretical
Cryptographic mechanisms to Enforce GDPR	[81]	Theoretical
H. Security analysis		
Algorand DDoS vulnerability	[82]	Application
Proof-of-Parity framework	[83]	Application
I. Applied implementations		
Microgrid energy trading	[84]	Application
V2X blockchain security	[64]	Application
IoT light node optimization	[63]	Application

Below, we categorize prominent solutions based on their core architectural focus:

5.1 Sharding Solutions

Sharding techniques partition blockchain networks into parallel processing units to enhance throughput while preserving decentralization.

5.1.1 Sharding Throughput Gain

For k shards, each processing t_{shard} transactions per second (TPS), the total throughput is:

$$\text{TPS}_{\text{total}} = k \cdot \text{t}_{\text{shard}} \cdot (1 - \beta)\,. \tag{21}$$

where β is the cross-shard coordination overhead ($0 < \beta < 1$).

5.1.2 Security Analysis of Sharding

The probability of a shard being compromised by f Byzantine nodes is:

$$P_{\text{fail}} = \binom{n}{f} \left(\frac{f_{\text{global}}}{n_{\text{total}}} \right)^{f} \left(1 - \frac{f_{\text{global}}}{n_{\text{total}}} \right)^{n-f} \tag{22}$$

where f_{global} is the total malicious nodes in the network.

In [43], the authors introduced ELASTICO, a novel sharding protocol designed to overcome the scalability limitations of open blockchains like Bitcoin while ensuring security against Byzantine adversaries. The authors identified the critical challenge of achieving linear scalability in transaction throughput without compromising decentralization or security, a problem unsolved by existing consensus protocols such as Nakamoto consensus or classical Byzantine fault-tolerant (BFT) approaches. The core innovation of ELASTICO lay in its partitioning of the mining network into smaller committees, each processing disjoint transaction shards in parallel, with the number of committees scaling near-linearly with the network's computational power. The protocol operated in five key steps: (1) identity establishment via proof-of-work (PoW) to limit Sybil attacks, (2) committee formation and overlay setup using a directory committee to reduce communication overhead, (3) intra-committee consensus employing PBFT to agree on transaction shards, (4) final consensus by a designated committee to aggregate shards into a single blockchain update, and (5) epoch randomness generation to ensure unbiased committee assignments in subsequent epochs. The authors implemented ELASTICO as an extension of Bitcoin's codebase, adding approximately 5000 lines of C++, and evaluated its performance on Amazon EC2 with networks of up to 1600 nodes. The experiments demonstrated near-linear scalability, with throughput increasing from 1 block per epoch (100 nodes) to 13.5 blocks (1600 nodes), while maintaining constant per-node bandwidth usage (~5 MB) and tolerating up to 1/4 Byzantine adversaries. Key performance metrics included transaction throughput, latency, message complexity ($\mathcal{O}(nc + nc^3)$), and bandwidth efficiency, all of which confirmed the protocol's theoretical claims. The final results showed a 4-order-of-magnitude improvement over Bitcoin's throughput when extrapolated to Bitcoin's scale, achieving 10,000 blocks per epoch. Security proofs established probabilistic agreement, validity, and randomness guarantees, with lemmas bounding adversarial influence (e.g., Lemma 2 ensured honest majority in committees). However, the work assumes partial synchrony and reliable committee formation, which may not hold in highly dynamic or adversarial network conditions. The security protocol's heavily relies on the assumption of a static, round-adaptive adversary and does not fully address real-world network churn or eclipse attacks.

In the study [65], the authors explored the scalability challenges inherent in blockchain technology, particularly focusing on the inefficiencies of trustless peer-to-peer networks that result in slow transaction processing speeds, as exemplified by Bitcoin's mere three transactions per second (TPS). They identified the root cause as the suboptimal propagation and validation of information across decentralized nodes, which creates bottlenecks due to cryptographic operations at each hop, high performance variance among nodes, and inefficient network paths. To address this, they proposed leveraging cloud-delivery networks (CDNs), such as Akamai and YouTube, which have successfully scaled other domains (e.g., web and video delivery) by optimizing data distribution. However, the centralized nature of CDNs conflicts with blockchain's decentralized ethos, raising concerns about censorship and trust. As a solution, the authors introduced a Blockchain Distribution Network (BDN), a provably neutral network that decouples authority from infrastructure, ensuring scalability without compromising decentralization. The BDN employed several

key mechanisms: encrypted blocks to prevent content-based censorship, indirect relay to obscure block origins, and continuous auditing via test blocks to detect and mitigate discriminatory behavior. Additionally, it optimized performance through transaction caching (reducing block size by indexing transactions), cut-through routing (accelerating data transmission), and mitigating the transaction incast problem (minimizing redundant data reception). The authors compared their approach with existing scaling solutions, such as off-chain methods (e.g., the Lightning Network) and on-chain techniques (e.g., sharding), arguing that the BDN complements these methods by fundamentally improving the network layer. They further theorized that BDN could dramatically enhance scalability by leveraging optimized network-layer techniques like cut-through routing, transaction caching (reducing block sizes by over 100x), and eliminating the incast problem. Additionally, they suggested that, with dedicated infrastructure (e.g., optical networks), BDN could achieve microsecond-scale latencies, similar to modern data centers. Performance evaluation highlighted the BDN's potential to significantly increase throughput and reduce latency, reinforcing the possibility of achieving microsecond-scale latencies in dedicated infrastructures. The research concluded that provably neutral clouds, like the BDN, offer a viable path to scaling blockchain networks while preserving their decentralized nature, provided the blockchain ecosystem can trust the underlying network infrastructure. However, a key limitation of the proposed BDN is its reliance on continuous auditing and the potential complexity of maintaining neutrality in practice.

Hung Dang et al. [44] addressed the critical scalability challenges in blockchain systems by proposing a sharding-based approach tailored for permissioned blockchains, aiming to achieve high transaction throughput while supporting general workloads beyond cryptocurrency applications. The authors identified three primary challenges in applying traditional database sharding techniques to blockchains: scaling Byzantine Fault Tolerance (BFT) consensus protocols, ensuring secure and efficient shard formation, and enabling secure distributed transactions even with malicious coordinators. To tackle these challenges, they leveraged trusted execution environments (TEEs), specifically Intel SGX, to enhance the performance of BFT consensus protocols by eliminating equivocation, thereby allowing a committee of n nodes to tolerate up to $\frac{n-1}{2}$ Byzantine failures, a significant improvement over the traditional $\frac{n-1}{3}$ threshold. They introduced optimizations such as separating message queues and removing redundant request broadcasts to reduce communication overhead, resulting in their AHL+ protocol, which outperformed existing solutions like PBFT and AHLR in terms of throughput and scalability. For shard formation, the authors designed a TEE-assisted protocol using a trusted randomness beacon to securely and efficiently assign nodes to shards, ensuring that no shard could be compromised by adversarial nodes while also enabling smaller committee sizes (e.g., 80 nodes for a 25% adversarial power) compared to prior works like OmniLedger, which required 600-node committees. Additionally, they proposed a distributed transaction protocol combining two-phase locking (2PL) and two-phase commit (2PC) to handle cross-shard transactions securely, even with malicious coordinators, by employing a Byzantine fault-tolerant reference committee to coordinate transactions. The authors conducted extensive evaluations on both a local 100-node cluster and a large-scale Google Cloud Platform (GCP) setup with over 1400 nodes across eight regions, demonstrating that their sharded blockchain achieved a throughput of over 3000 transactions per second, capable of handling Visa-level workloads—the highest reported in a realistic environment at the time. Their results showed linear scalability with the number of shards and highlighted the effectiveness of their optimizations, such as reducing message drops and improving fault tolerance.

In the study [52], authors proposed a novel blockchain architecture designed to address key industrial challenges such as privacy, scalability, and governance in permission-based blockchain systems. They introduced the concept of "satellite chains," which are interconnected yet independent subchains that operate in parallel, each maintaining its own private ledger and consensus protocol tailored to the needs

of its stakeholders. This design allowed nodes to join multiple satellite chains simultaneously, ensuring privacy by restricting transaction visibility only to relevant participants while enabling cross-chain asset transfers without compromising security. The architecture also incorporated a regulatory framework where regulators could enforce policies across all satellite chains using smart contracts, specifically through a ”policy directory contract” that managed and deployed policy checks dynamically. To validate their approach, the authors integrated their solution with Hyperledger Fabric v0.6, adapting its structure to support multiple ledgers, cross-chain transactions, and policy enforcement mechanisms. They extended Fabric's functionality by introducing data structures like chain-to-consensus and chain-to-peers maps to manage satellite chains and their participants, and implemented a policy directory chaincode to automate policy deployment and validation. The integration demonstrated the feasibility of their architecture, showcasing its ability to enhance scalability by allowing parallel consensus protocols and improving privacy through selective transaction visibility. The authors highlighted that their solution effectively realized blockchain sharding based on node relationships, making it suitable for industrial applications like trade finance and supply chain management. However, the work does not provide extensive empirical results or benchmarks to quantify the performance gains or overheads of their architecture.

The research article [45], authored by Mahdi Zamani et al., introduced RapidChain, a novel sharding-based public blockchain protocol designed to address the scalability and performance limitations of existing blockchain systems. The authors identified key bottlenecks in previous sharding-based protocols, such as linear communication overhead per transaction, low fault resiliency (e.g., 1/4 or 1/8), and reliance on trusted setups, which hindered their practicality for mainstream payment systems. RapidChain proposed a fully sharded architecture that partitioned the network into smaller committees operating in parallel, achieving sublinear communication overhead, higher Byzantine fault resiliency (up to 1/3 of participants), and eliminating the need for trusted setups. The protocol employed several innovative techniques, including an optimal intra-committee consensus algorithm based on synchronous Byzantine consensus, a novel gossiping protocol (IDA-Gossip) for efficient large block propagation, and a provably secure reconfiguration mechanism inspired by the Cuckoo rule to handle dynamic membership changes. Additionally, RapidChain introduced a fast cross-shard verification method leveraging Kademlia-inspired routing to minimize inter-committee communication and a decentralized bootstrapping protocol that avoided the quadratic message complexity of previous solutions. The authors implemented a prototype of RapidChain and evaluated its performance in a simulated network of up to 4000 nodes, demonstrating significant improvements over state-of-the-art protocols like Elastico and OmniLedger. RapidChain achieved a throughput of over 7300 transactions per second with a confirmation latency of approximately 8.7 s, while maintaining a high time-to-failure of over 4500 years. The evaluation also highlighted the protocol's efficiency in handling cross-shard transactions, storage scalability, and reconfiguration latency. Despite its advancements, RapidChain's reliance on synchronous communication during intra-committee consensus limits its responsiveness to network delays.

In another study [51], the authors proposed an innovative solution to Bitcoin's scalability challenges by introducing a mechanism to partition the Unspent Transaction Output (UTXO) set and split the blockchain into multiple sub-chains. The core idea revolved around ”split events,” where the UTXO space and mempool were divided deterministically based on scriptPubKey hashes, creating independently operating sub-chains that allowed multiple blocks to be mined simultaneously during each block interval. This approach significantly increased transaction throughput while preserving Bitcoin's decentralized nature. To ensure consistency across sub-chains, the authors introduced an eigenchain, a secondary blockchain that stored block headers from all sub-chains, requiring miners to perform atomic mining—simultaneously producing blocks for each sub-chain and the eigenchain—thereby maintaining security and preventing

manipulation. A key innovation was the introduction of half nodes, lightweight nodes that tracked only one sub-chain and the eigenchain, reducing bandwidth and storage requirements while still enabling transaction verification. This addressed a major decentralization concern, as it allowed users in low-resource environments to participate in the network without running full nodes. The work also detailed transaction handling post-split, including Hashed Time-Lock Contracts (HTLCs) for atomic cross-sub-chain payments and eigentransactions for secure fund transfers between sub-chains. The performance evaluation compared Split-Scale with existing solutions like Segregated Witness (SegWit) and Bitcoin-NG, demonstrating that it offered exponential scalability (Nx with each split event) while maintaining decentralization. Miners benefited from increased fee collection across all sub-chains, and half nodes ensured that network participation remained accessible. The results showed that Split-Scale could achieve higher throughput without compromising security or decentralization, making it a promising alternative to current scaling approaches. The complexity of managing multiple sub-chains and the need for consensus on split events remain challenges.

5.2 Layer-2 Scaling Solutions

Layer-2 solutions refer to off-chain protocols and secondary networks that enhance throughput while leveraging base-layer security.

The research article authored by Jason Teutsch et al. [46] introduced TrueBit, a scalable verification solution designed to address the computational limitations of blockchain systems like Ethereum and Bitcoin, which, despite their vast mining power, struggle with processing and verifying transactions efficiently due to the Verifier's Dilemma—a scenario where miners skip verification to avoid falling behind in the mining race. The authors proposed a two-layer system: a dispute resolution layer employing an interactive "verification game" to pinpoint computational errors through iterative rounds of challenge and response, and an incentive layer that financially motivates participants (Solvers and Verifiers) to perform and verify computations correctly. The verification game relied on Merkle trees and binary search to isolate disputed computation steps, ensuring Judges (Ethereum miners) could resolve disputes with minimal computational effort. The incentive layer incorporated mechanisms like forced errors, jackpot payouts, taxes, and deposits to ensure Solvers and Verifiers acted honestly, with forced errors occurring randomly to incentivize consistent verification. The work evaluated the system's efficiency by analyzing the runtime and security of the verification game, demonstrating that the Judges' workload remained manageable, with the total verification time scaling logarithmically with task complexity. The performance was further validated through economic incentives, ensuring that rational participants would not deviate from the protocol due to the high costs of cheating and the rewards for honest participation. The results showed that TrueBit enabled secure, trustless outsourcing of complex computations to Ethereum smart contracts, bypassing the gasLimit constraint and supporting applications like decentralized mining pools, cross-blockchain currency transfers, and scalable transaction throughput. The system's adaptability was highlighted by its compatibility with existing Ethereum infrastructure and its potential for future optimizations, such as specialized verification games for specific tasks. However, the work's limitation is that the security and efficiency of TrueBit degrade for extremely complex or big data tasks due to the impracticality of the verification game's overhead in such scenarios.

Anonymous Multi-Hop Locks (AMHLs) [47] have been introduced as a novel cryptographic primitive to address scalability and privacy issues in Payment Channel Networks (PCNs), such as the Lightning Network. The authors began by identifying a new attack, termed the "wormhole attack," which allows malicious users to steal fees from honest intermediaries in PCNs, demonstrating vulnerabilities in existing systems like the Lightning Network and Raiden Network. To mitigate this, they formally defined AMHLs, a cryptographic tool enabling secure and privacy-preserving multi-hop payments, and provided several provably secure constructions compatible with most cryptocurrencies, including script-based (using homomorphic one-way

functions) and scriptless (using ECDSA signatures) implementations. The scriptless ECDSA-based solution was particularly significant as it resolved a long-standing open problem in the field and was subsequently implemented by Lightning Network developers. The authors conducted a rigorous security analysis using the Universal Composability (UC) framework, ensuring their constructions were secure against concurrent executions and composable with other protocols. They also established a lower bound on communication complexity, proving that an extra round of communication is necessary for secure transactions to prevent wormhole attacks. Performance evaluations on commodity hardware showed that AMHL operations were highly efficient, with computation times under 100 ms and communication overhead below 500 bytes, even in worst-case scenarios. The practical impact of their work was underscored by the Lightning Network's adoption of their ECDSA-based AMHLs, which improved security, privacy, and interoperability while maintaining scalability. Additionally, the authors demonstrated the versatility of AMHLs by extending their use to atomic swaps and interoperable PCNs, enabling cross-currency transactions. The performance results highlighted the feasibility of their approach, with the generic construction requiring minimal gas (350,849 units per hop in Ethereum) and scriptless constructions eliminating the need for additional scripts, reducing transaction size and blockchain load. Despite these advancements, a key limitation of this work is that the proposed constructions do not support adaptive corruption queries, leaving the security of dynamically corruptible environments an open question.

BloXroute [13] is a Blockchain Distribution Network (BDN) designed to address the scalability limitations of blockchain systems while preserving decentralization and trustlessness. The authors identified that existing blockchains, such as Bitcoin, suffer from low throughput (e.g., 2.94 TPS compared to Visa's 2000 TPS) due to inefficiencies in peer-to-peer (P2P) propagation models, where block propagation times increase linearly with block size, leading to forks, security vulnerabilities, and centralization pressures. To overcome these challenges, the work proposed a global, protocol-agnostic BDN that leverages high-capacity, low-latency infrastructure to accelerate block propagation without requiring trust in the network itself. Key innovations included encrypted blocks to ensure neutrality, indirect relay mechanisms to obscure block origins, and test-blocks for continuous auditing, ensuring the BDN could not discriminate based on content, origin, or destination. The system employed cut-through routing and system-wide caching to enable gigabyte-sized blocks and reduce propagation delays, theoretically increasing throughput by over three orders of magnitude (e.g., supporting 200,000 TPS with conservative estimates). Performance evaluation demonstrated that bloXroute could reduce block propagation times dramatically, enabling blockchains to scale to Visa-like throughput by simply adjusting block size and inter-block intervals, while maintaining security and decentralization. The work also introduced BLXR, an ERC20 token, to align incentives across the ecosystem by distributing revenues from transaction fees to token holders, with projected annual revenues exceeding $3.1 billion at scale. The results highlighted bloXroute's ability to close the gap between decentralized blockchains and traditional payment systems, unlocking applications like microtransactions and IoT automation. However, the system's reliance on voluntary payments for sustainability and the potential for collusion between the BDN and a subset of peers remain limitations.

Joseph Poon and Thaddeus Dryja [54], proposed a decentralized solution to Bitcoin's scalability problem by introducing the Lightning Network, a system of micropayment channels that enable instant, high-volume transactions without overburdening the blockchain. The authors identified the limitations of Bitcoin's blockchain, such as its inability to handle global transaction volumes due to block size constraints, which lead to centralization risks and high fees. To address this, they designed a network of bidirectional payment channels where transactions occur off-chain, only settling on the blockchain when necessary, thus reducing congestion and maintaining decentralization. The core innovation involved the use of Revocable Sequence Maturity Contracts (RSMCs) and Hashed Timelock Contracts (HTLCs) to ensure security and

trustlessness. RSMCs allowed parties to update channel states while penalizing dishonest behavior by revoking outdated transactions, while HTLCs facilitated multi-hop payments across the network using hash-based conditions and decrementing timelocks to ensure atomicity. The research detailed the construction of these contracts, including the need for a malleability fix (SIGHASH_NOINPUT) to prevent transaction ID mutations and enable secure off-chain agreements. The authors also discussed key management strategies, such as hierarchical deterministic wallets, to minimize storage overhead and ensure scalability. Performance evaluation highlighted the network's potential to support billions of transactions with minimal blockchain footprint, enabling micropayments, instant transactions, and cross-chain interoperability. The final result demonstrated that the Lightning Network could achieve Visa-like transaction throughput (47,000 tps) while retaining Bitcoin's decentralized security model, with fees asymptotically approaching zero due to off-chain settlement. The system's value lay in its ability to scale Bitcoin for global adoption without compromising its core principles. The work relies on soft-fork upgrades to Bitcoin, such as SIGHASH_NOINPUT and OP_CHECKSEQUENCEVERIFY, which may face implementation challenges or resistance from the community.

5.3 Emerging Consensus Paradigms

Recent advancements in consensus design aim to address the trilemma through novel architectures:

- **Narwhal & Tusk (Aptos):** Decouples transaction dissemination (Narwhal) from consensus (Tusk), achieving 160,000 TPS in benchmarks [85]. While Narwhal's mempool ensures availability via directed acyclic graphs (DAGs), Tusk leverages randomized leader elections for asynchronous safety. Trade-offs include increased memory demands for DAG storage.
- **Snowman++ (Avalanche):** Optimizes the Snow family of protocols for linear blockchains, combining DAG-based voting with a totally ordered ledger. Its *decision threshold* mechanism reduces latency to 1–2 s while tolerating 40% Byzantine nodes [86]. However, validator incentives remain centralized in early deployments.
- **Proof of History (PoH-Solana):** Uses cryptographic timestamps (SHA-256 chains) as a verifiable clock, enabling parallel transaction processing. PoH reduces consensus overhead by 65% compared to PBFT [87], but depends on leader nodes for sequencing—creating single points of failure during network partitions.

5.4 Consensus Mechanism Innovations

Consensus mechanisms denote novel approaches to achieving agreement while balancing trilemma constraints. The general working mechanism of consensus algorithms is depicted using Fig. 6.

Monu Chaudhary et al. [76] explored the challenges posed by the blockchain trilemma, which highlights the difficulty in simultaneously achieving decentralization, security, and scalability in blockchain networks. The authors provided a comprehensive analysis of Layer 1 (base layer) and Layer 2 (off-chain) solutions aimed at addressing these challenges. They began by explaining the foundational concepts of blockchain, including consensus mechanisms like Proof of Work (PoW) and Proof of Stake (PoS), and elaborated on how these mechanisms contribute to the trilemma. The study categorized scalability solutions into Layer 1 approaches, such as increasing block size, adopting alternative consensus algorithms (e.g., PoS), sharding, and Directed Acyclic Graphs (DAGs), and Layer 2 solutions, including channels (e.g., Lightning Network), sidechains, rollups, and cross-chain protocols. The authors performed a comparative analysis of these solutions, evaluating their impact on transaction speeds, implementation complexity, and trade-offs between decentralization, security, and scalability. They utilized real-world data, such as transaction speeds from blockchain networks like Bitcoin, Ethereum, and Layer 2 platforms like Polygon and Solana, to illustrate the

performance improvements offered by these solutions. For instance, Ethereum 2.0's theoretical transaction speed of 100,000 TPS and Solana's 3000 TPS were highlighted as significant advancements over Bitcoin's 7 TPS and Ethereum 1.0's 20 TPS. The results demonstrated that Layer 2 solutions, such as the Lightning Network and sidechains, were easier and faster to implement compared to Layer 1 modifications, which often required hard forks and extensive protocol changes. However, the authors noted that despite these advancements, no solution fully resolved the trilemma, as trade-offs between the three pillars persisted. The authors concluded the study by emphasizing the need for further research to achieve a harmonious balance between decentralization, security, and scalability. A key limitation of the work is that the work does not propose a novel solution to entirely solve the blockchain trilemma but rather synthesizes and evaluates existing approaches.

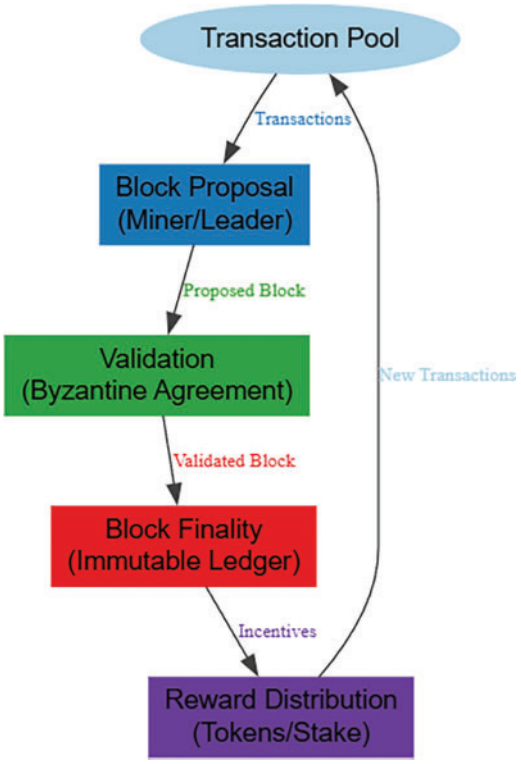

Figure 6: General working procedure of consensus mechanisms

In the scholarly article [57], the authors introduced Chameleon, a scalable and adaptive permissioned blockchain architecture designed to address key challenges in blockchain systems, including scalability, security, and resource utilization. The authors structured their solution into four layers: the control and authentication layer, responsible for issuing certificates and load balancing; the cloud storage layer, which offloaded historical block data to local, edge, or core clouds to reduce node storage burdens; the consensus and processing layer, where nodes were partitioned into different areas, each capable of running tailored consensus protocols; and the access layer, enabling clients to register and interact with the system. To enhance security, the work proposed RLSCV (Random Leader Selection based on Credit Value), an improved Byzantine consensus protocol where leaders were selected probabilistically based on their credit scores—calculated as $\log_2(B_n)$ (with B_n being the number of blocks a node has produced as a leader)—ensuring that honest nodes had a higher chance of leading while preventing predictability-based attacks like

DoS. For scalability and efficiency, the system incorporated QoS-aware transaction processing, classifying transactions into four types (ordinary, cross-area, cooperative, and sub-area) with priority levels (network control, instant processing, accelerated, and ordinary), enabling dynamic load balancing. The cloud storage integration allowed nodes to store only recent epoch data (e.g., one day or one week) while archiving older blocks in distributed clouds, significantly reducing storage overhead. To evaluate performance, the authors conducted simulations in MATLAB, modeling transaction arrivals using a Poisson process and testing the load balancing mechanism under varying transaction rates. The experiments assumed each area had a processing capacity of 400 transactions per second (TPS), a realistic benchmark derived from tests on Hyperledger Fabric with PBFT consensus. Three key scenarios were analyzed: moderate overload (400 TPS in Area-2), where the system redistributed transactions to Area-3, dropping Area-2's load from 1.0 to 0.8 and increasing Area-3's load from 0.3 to 0.5; high overload (600 TPS in Area-2), where transactions were offloaded to Area-3 and Area-5, reducing Area-2's load to 0.8 while raising Area-3 and Area-5's loads to 0.6 and 0.4, respectively; and extreme overload (800 TPS in Area-2), where transactions were distributed across Area-1, Area-3, and Area-5, stabilizing Area-2's load at 0.8 and adjusting the assisting areas to 0.5, 0.6, and 0.5, respectively. The results proved that Chameleon's load balancing algorithm effectively optimized resource utilization, preventing bottlenecks and maintaining performance even when transaction rates doubled the baseline capacity (800 TPS vs. 400 TPS). The credit-based leader selection (RLSCV) also ensured security by preventing Sybil and DoS attacks, while cloud storage integration reduced node storage requirements by archiving older blocks off-chain. However, the work remains a proof-of-concept without real-world deployment, and the overhead of cross-area transaction synchronization under load balancing needs further investigation. The system's reliance on a centralized control and authentication layer (CA) introduces a potential bottleneck and single point of failure.

Jian Liu et al. [12] proposed FastBFT, a fast and scalable Byzantine fault-tolerant (BFT) protocol designed to address the inefficiencies and scalability limitations of existing BFT protocols, which typically suffer from $O(n^2)$ message complexity, making them impractical for large-scale networks. The authors leveraged trusted execution environments (TEEs), such as Intel SGX, combined with a novel message aggregation technique using lightweight secret sharing to reduce the message complexity to $O(n)$, significantly improving performance and scalability. FastBFT incorporated several optimizations, including optimistic execution, a tree-based communication topology to distribute computational and communication loads, and a failure detection mechanism to handle non-primary faults efficiently. The protocol operated in two modes: a normal-case mode for optimal performance and a fallback mode(classical BFT with message aggregation) for handling persistent faults, ensuring robustness under varying conditions. The authors implemented FastBFT and evaluated its performance against existing BFT protocols like Zyzzyva, MinBFT, CheapBFT, and XPaxos, demonstrating that FastBFT achieved significantly higher throughput and lower latency, especially as the network size grew. For instance, with 199 replicas, FastBFT processed 370 operations per second for 1 KB payloads, outperforming Zyzzyva by a factor of 6, and scaled efficiently even for larger payloads (1 MB), achieving 260 times higher throughput than Zyzzyva. The performance gains were attributed to the reduction in communication overhead and the efficient use of TEEs for secret sharing and aggregation. The results confirmed that FastBFT struck an optimal balance between performance and resilience, making it a suitable candidate for next-generation blockchain systems, with the potential to process over 100,000 transactions per second under realistic assumptions.

In [55], authors presented a novel consensus model aimed at addressing the blockchain trilemma—balancing decentralization, security, and scalability—by integrating advanced cryptographic techniques, stake management, and random leader selection mechanisms. The authors began by highlighting the limitations of existing consensus models, such as PoW and PoS, which often prioritize one aspect of the

trilemma at the expense of others. To overcome these challenges, they proposed a comprehensive framework that combined Verifiable Random Functions (VRF) for unbiased slot leader selection, dynamic stake recalibration based on reputation and economic performance, and batch agreement systems for efficient transaction processing. The methodology involved establishing a decentralized network where nodes were assigned initial stakes and cryptographic key pairs, followed by an epoch-based structure for synchronization and stake adjustment. The consensus process included transaction gathering by slot leaders, block proposal, validation through Honey Badger Byzantine Fault Tolerance (BFT) and other cryptographic techniques, and fault tolerance mechanisms to mitigate malicious activity. The authors also incorporated sharding and layer-2 solutions like optimistic rollups to enhance scalability and interoperability across blockchain platforms. To evaluate their model, they analyzed security using the chain quality metric, comparing it with other consensus mechanisms like SHTB, PoP, UTB, and UDTB, and found their system outperformed most except PoP. Performance metrics demonstrated a transaction throughput of 119 TPS on average, with latency as low as 1.05 s for 400 transactions and 1.186 s for 800 transactions, showcasing robust scalability. The system's decentralization was validated through features like public accessibility, resilience to various attacks (e.g., 51% and Sybil attacks), and affordable validator node costs ($693). Despite these advancements, the paper acknowledged the need for real-world testing to confirm the model's practicality under diverse conditions. The research work basically relies on theoretical validation and requires extensive real-world implementation to assess its full potential.

The paper [56] introduced a novel blockchain consensus mechanism aimed at resolving the blockchain trilemma by simultaneously achieving security, scalability, and decentralization. The authors proposed an architecture integrating adaptive stake recalibration to dynamically adjust node influence based on historical performance, stake transfers, and economic metrics, alongside epoch-based operations for structured consensus. Cryptographic techniques such as Schnorr Verifiable Random Functions (VRF) ensured secure and unbiased slot leader selection, while zero-knowledge proofs (zk-SNARKs) enhanced transaction privacy and validation efficiency. Scalability was addressed through sharding for parallel transaction processing and Layer-2 rollups for off-chain aggregation, combined with Merkelized Abstract Syntax Trees (MAST) to optimize smart contract execution. Security mechanisms included Practical Byzantine Fault Tolerance (PBFT) for batch agreement, anomaly detection algorithms, and redundancy measures with erasure codes. The system employed a reputation-based stake distribution model to prevent centralization, incentivizing positive behavior through economic rewards and penalties. For evaluation, the authors conducted extensive experiments on a 48-node network, comparing performance against Proof of Work (PoW), Proof of Stake (PoS), Delegated PoS (DPoS), PBFT, and Proof of Authority (PoA). Results demonstrated a throughput of 1700+ transactions per second (TPS) with latency between 15–90 ms, surpassing PoW (7 TPS) and PoA (232 TPS). The system maintained a low average CPU usage of 16.1% compared to PoW (63.2%) and PBFT (24.1%), while achieving a decentralization score of 7.182, competitive with Bitcoin (7.909) and Ethereum (7.656). Security evaluations showed resilience against double-spending attacks (22-min confirmation time at 45% adversarial stake) and negligible fork probability (analyzed via binomial distribution). A limitation of the work is that the scalability and decentralization claims remain theoretical, requiring validation in real-world, large-scale deployments.

5.5 Network and Protocol Optimizations

Many state-of-the-art works have brought major improvements in network-layer propagation and transaction processing efficiency.

The article authored by Kaiwen Zhang et al. [77] presented a comprehensive exploration of distributed ledger technology (DLT) and blockchain systems, aiming to address the challenges of dependability,

scalability, and pervasive adoption. The authors began by highlighting the transformative potential of blockchains across various industries, emphasizing their ability to provide transparency, immutability, and security without centralized control. They identified key pain points hindering widespread adoption, such as trust issues, integration difficulties, and scalability limitations, and proposed a structured research landscape to guide future efforts. The reseach introduced the DCS properties—Decentralization, Consistency, and Scalability—as a framework analogous to the CAP theorem, illustrating the inherent trade-offs in blockchain design. A taxonomy of blockchain applications was presented, categorizing them into three generations: Blockchain 1.0 (cryptocurrency), 2.0 (decentralized applications or DApps), and 3.0 (pervasive applications like eHealth and supply chain management), each with unique challenges and research directions. The authors further decomposed blockchain platforms into six layers—Application, Modeling, Contract, System, Data, and Network—providing a detailed reference architecture to analyze and improve blockchain systems. To evaluate performance, the work compared existing platforms like Bitcoin, Ethereum, and Hyperledger, demonstrating how each prioritized different DCS properties; for instance, Bitcoin and Ethereum emphasized Decentralization and Consistency at the cost of Scalability, while Hyperledger achieved higher throughput by sacrificing some decentralization. The final results underscored the need for tailored blockchain solutions, as no single design could satisfy all requirements across applications, and the authors advocated for continued research in areas like consensus algorithms, smart contract security, and interoperability. The value of the work lay in its systematic classification of blockchain research, offering a roadmap for future innovations to enhance dependability, scalability, and adoption. A key limitation of the work is that it does not provide empirical validation of the proposed frameworks or quantify the trade-offs between DCS properties in real-world deployments.

Blockchain systems face critical challenges in scalability and throughput, especially for lightweight nodes like IoT devices that cannot store the full blockchain due to its size. To address this, the authors [63] proposed an innovative solution by designing a high-performance caching system implemented on an FPGA-based network interface controller (NIC) to offload and accelerate blockchain data access. They focused on optimizing the caching mechanism by developing a customized SHA-256 hash core tailored for efficient blockchain operations, which reduced redundant hashing executions and significantly improved performance. To integrate their system with real-world blockchain applications, the authors utilized Jansson and Curl libraries to interface with the Bitcoin core, ensuring seamless communication and data handling. The performance evaluation of their system demonstrated remarkable improvements, with the results showing a 103-fold increase in throughput performance during cache hits, highlighting the efficiency of their design. Additionally, the FPGA implementation offered advantages such as minimal work area utilization, low power consumption, and high performance, making it a practical solution for enhancing blockchain scalability. The authors meticulously evaluated their system by measuring throughput, power consumption, and resource utilization, providing a comprehensive analysis of its capabilities. The success of their approach was evident in the substantial performance gains and the system's ability to handle the workload of lightweight nodes effectively.

Blackchain [64] is a novel blockchain-based system designed to enhance accountability and scalability in Vehicle-to-X (V2X) communication, particularly by addressing the challenges of misbehavior detection and revocation in resource-constrained environments. The authors identified the limitations of traditional Event Data Recorders (EDRs) and centralized Public Key Infrastructures (PKIs), such as high storage costs, lack of tamper-proofing, and centralized trust in misbehavior authorities (MAs). To overcome these issues, they introduced a hierarchical consensus mechanism leveraging distributed ledger technology, where vehicles dynamically formed clusters to agree on local states, which were then propagated to Road-Side Units (RSUs) for further aggregation. These RSUs, organized into smaller groups, performed Byzantine

Fault Tolerant (BFT) consensus to validate and forward decisions to MAs, which ultimately published the results on a global, permissionless Blockchain for transparency and public verifiability. The system ensured accountability by allowing all participants to audit revocation decisions and evidence, thereby reducing reliance on a single trusted entity. The authors evaluated the performance of Blackchain by focusing on its ability to handle high message frequencies (10 Hz per vehicle) and churn in VANETs, demonstrating that hierarchical clustering and permissioned blockchains significantly reduced the computational overhead and latency compared to a naive, fully decentralized approach. The results indicated that the proposed system achieved scalable and efficient misbehavior detection and revocation while maintaining privacy through pseudonymous certificates and partial validity periods. The performance was validated through theoretical analysis, highlighting the system's ability to balance transparency, security, and scalability in large-scale vehicular networks. However, the stability of vehicle clusters and the guarantees of hierarchical consensus compared to full consensus remain open challenges.

The paper [61] proposed Matching-Gossip, a novel blockchain broadcast protocol designed to address the network layer bottleneck in the GBT-CHAIN framework by resolving the topological mismatch of traditional Gossip protocols and optimizing performance under the CAP trilemma. The authors introduced two mechanisms: (1) a *direct neighbor node discovery mechanism* that aligned the logical overlay network with the hypercube physical topology by maintaining neighbor lists based on physical proximity (measured via network latency), reducing link duplication, and (2) a *state broadcast mechanism* that utilized UUID-tagged state bits to track message reception, preventing redundant transmissions. They evaluated Matching-Gossip against Gossip in small-scale simulations (4–32 nodes on two physical servers) and large-scale real-world experiments (16–1024 nodes across global cloud servers), measuring convergence time, network load, and convergence rate. Results showed Matching-Gossip reduced average convergence time by 40% (e.g., from 50 to 30 ms for 32 nodes) and slashed network load by 60%–75% (e.g., from 5000 to 2000 packets for 32 nodes, and from 200,000 to 50,000 packets for 1024 nodes). In large-scale tests, convergence rates under a 10-dimensional hypercube topology improved significantly, with Matching-Gossip achieving near-linear scaling. The protocol demonstrated compatibility with hypercube physical topologies, enhancing partition tolerance and reducing redundant traffic. Performance gains were attributed to constrained neighbor selection and state-based message filtering. A limitation of the study is that it does not validate the protocol in networks exceeding 1024 nodes or account for cross-shard transaction complexities in heterogeneous blockchain systems.

The paper [62] addressed the Blockchain Trilemma—the challenge of simultaneously achieving security, decentralization, and scalability—by introducing a novel *time-beacon* scheme that restructures blockchain architecture into a hierarchical system comprising a Time-Beacon Chain (TBC) and Business Chains (BCs). The authors identified that traditional blockchain security relies on consensus mechanisms where block security depends on the size of block producers, leading to scalability-decentralization trade-offs. Their solution decoupled block security from the Business Chain by anchoring block publication times to a decentralized Time-Beacon Chain, which cryptographically guarantees the temporal authenticity of blocks through Merkle-root-linked timestamp requests. This enabled horizontal scaling of Business Chains without reducing block producer sizes, thereby preserving security and decentralization. The proposed architecture allowed multi-level scaling via Beacon Sub-Chains, exponentially amplifying throughput while maintaining time assurance. To validate the approach, the authors developed *EasyChain*, a prototype integrating Ethereum smart contracts as the TBC and PBFT-based sharded Business Chains. Experiments involved replaying 3 million Ethereum transactions across 9 high-performance nodes, demonstrating near-linear global throughput scaling (300 TPS per shard) with increasing shard count, stable median transaction latency (4 s block intervals), and manageable cross-chain confirmation times ($2t_c + \alpha$, where α was optimized

to 18 epochs for <10% cancellation rates). Performance analysis revealed optimal throughput alignment with shard count and transaction arrival rates, achieving scalability up to 910 sub-chains using Ethereum's smart contract storage. Security analysis showed the time-beacon scheme mitigated 51% attacks, double-spending, and other risks by relying on the TBC's immutability, while decentralization was maintained through lightweight node requirements. A key limitation of the work is that the Time-Beacon Chain's inherent throughput constraints may still pose scalability bottlenecks in long-term deployments despite multi-level hierarchical designs.

5.6 Cryptographic Enhancements and Privacy

These solutions leverage advanced cryptography to enhance security/scalability trade-offs.

The paper [66] introduced *Bounty 3.0*, a blockchain and Zero-Knowledge Proof (ZKP)-based solution addressing the "Bug Bounty Trilemma"—a challenge balancing security, privacy, and rewards in traditional bug bounty programs. The authors proposed a decentralized architecture leveraging blockchain for immutable, transparent program management and smart contracts for automating reward distribution and validation processes, while zk-SNARKs ensured privacy by allowing security researchers to prove vulnerability ownership without disclosing sensitive details. Key components included a token-based reward system (using stablecoins or ERC20 tokens), a modular smart contract structure (e.g., Program Factory, Bounty Program, and Verifier contracts), and an off-chain database for confidential issue details. The implementation strategy utilized Ethereum Layer 2 solutions with ZK-Rollups to enhance scalability and reduce transaction costs. The authors conducted a comparative analysis between traditional bug bounty platforms (e.g., HackerOne) and Bounty 3.0, highlighting improvements in decentralization, privacy (via wallet-based anonymity), on-chain validation transparency, and tamper-proof reward distribution. Results demonstrated enhanced security through immutable program histories, reduced privacy risks via ZKPs, and flexible tokenized rewards. The evaluation emphasized technical feasibility but lacked empirical performance metrics such as transaction throughput or latency. A limitation of the approach is its reliance on off-chain data storage and the scalability constraints inherent to current ZK-Rollup implementations, which may affect real-world adoption under high-volume conditions.

The paper [67] explored the application of Zero-Knowledge Proofs (ZKPs) to address the blockchain trilemma—balancing decentralization, security, and scalability—through a multivocal literature review (MLR) encompassing academic and grey literature. The authors systematically analyzed 51 sources (30 academic, 21 grey) by developing search strings, applying inclusion/exclusion criteria, and performing backward/forward searches across databases such as ACM Digital Library, arXiv, and Ethereum community resources. They evaluated the quality of grey literature using predefined criteria and structured findings into three epochs: the genesis of ZKPs (1985–2013), early blockchain privacy enhancements (2013–2020), and recent scalability solutions (2020–2023). The study identified that ZKPs enhance scalability by enabling off-chain computation (e.g., ZK-rollups reducing on-chain verification overhead) and improve security via integrity checks for encrypted transactions, as seen in protocols like Zcash and Ethereum's ZK-EVM. However, ZKPs shifted decentralization challenges to governance layers (e.g., ZK-service providers), creating centralized bottlenecks in rollup implementations. The authors validated their findings through thematic analysis of literature, highlighting SNARKs, STARKs, and Bulletproofs as key ZKP schemes with trade-offs in proof size, setup trust, and efficiency. Performance metrics, such as Ethereum's transition from 15–20 transactions per second (TPS) to ZK-rollups enabling ~2000 TPS, demonstrated scalability gains, while privacy-focused blockchains like Monero and Zcash showcased ZKP-driven confidentiality. The work concluded that ZKPs resolve scalability and security dimensions of the trilemma but necessitate further

research on decentralization mechanisms. A limitation of the study is that it does not empirically validate the decentralization trade-offs of ZKP implementations in live blockchain ecosystems.

5.7 Hybrid and Modular Architectures

These architectures combine multiple approaches through layered or interconnected systems, yielding a comprehensive framework that leverages the strengths of each method.

The paper [48] presented *Trifecta*, a blockchain protocol designed to resolve the Blockchain Trilemma by simultaneously achieving decentralization, security, and scalability. The protocol leveraged three core innovations: (1) *block graph factorization*, which decomposed blockchain functionality into distinct proposer, transaction, and voter blocks to decouple security and scalability; (2) *coded Merkle trees*, enabling horizontal scaling via sharding while ensuring data availability through erasure coding and succinct fraud proofs; and (3) *work virtualization*, a mechanism to mimic Proof-of-Work (PoW) incentives in Proof-of-Stake (PoS) systems to mitigate the nothing-at-stake problem. Built atop the Prism protocol for vertical scaling, Trifecta employed a sharding architecture where nodes self-allocated to shards, maintaining consensus on proposer and voter blocks globally while processing transaction blocks locally. The authors implemented both PoW and PoS versions in Rust and evaluated performance on a 100-node Amazon EC2 testbed with a 4-regular network topology, achieving a throughput of 250,000 transactions per second (tps) and confirmation latencies of 20–30 s. Key results demonstrated linear scaling with shard count, constant per-node resource usage (e.g., 50.43% bandwidth for transaction blocks and 49.5% CPU for RocksDB operations), and resilience against adaptive adversaries controlling up to 50% of resources. Comparative analysis showed Trifecta outperformed Algorand and longest-chain protocols in throughput-latency tradeoffs, with latency remaining under one minute even at 40% adversarial power. A limitation of the work is its reliance on idealized network assumptions and the need for further validation under real-world adversarial conditions, such as Sybil attacks or collusion across shards.

Trent McConaghy et al. [68] introduced BigchainDB, a scalable blockchain database designed to bridge the gap between traditional distributed databases and blockchain technologies by combining the high throughput, low latency, and rich querying capabilities of modern distributed databases with the decentralized control, immutability, and digital asset management features of blockchains. The authors highlighted the limitations of traditional blockchains like Bitcoin, such as poor scalability (e.g., low throughput, high latency, and limited capacity), and contrasted these with the performance of distributed databases like Cassandra and RethinkDB, which excel in scalability but lack decentralization and immutability. BigchainDB was built on top of an existing distributed database (initially RethinkDB, with plans to support others like MongoDB), inheriting its scalability while adding blockchain-like characteristics through innovations such as decentralized control via a federation of voting nodes, immutability achieved through cryptographic signing and replication, and support for creating and transferring digital assets. The system architecture involved two primary components: a transaction backlog (S) for unordered transactions and a blockchain (C) for ordered, validated blocks, with the BigchainDB Consensus Algorithm (BCA) coordinating the movement of transactions between these components and enabling voting-based validation. The federation-based consensus model reduces decentralization compared to proof-of-work or proof-of-stake systems. The experimental results demonstrated BigchainDB's ability to achieve high scalability while maintaining blockchain properties. In throughput tests, the system exhibited linear scaling, reaching 1 million writes per second with 32 nodes, where each node contributed approximately 31,250 writes per second. This performance was achieved by distributing writes across shards and leveraging RethinkDB's soft durability mode, which acknowledged writes immediately after memory caching rather than waiting for disk commits. The latency analysis revealed that internal transaction confirmation times depended heavily on node

distribution—data-center-localized clusters achieved sub-millisecond latencies, while globally distributed nodes experienced higher latencies (≈1.35 s) due to network propagation delays. Capacity scaling was also linear, with each node adding 48TB of storage, enabling petabyte-scale databases. The system's immutability and tamper-resistance were ensured through cryptographic hashing (SHA3-256) and Ed25519 signatures, while decentralized control was maintained via a federated voting model where nodes reached majority consensus on block validity. Fault tolerance was tested under benign and Byzantine failure scenarios, with the system recovering from node failures by reassigning transactions and revalidating blocks. However, the experiments also highlighted limitations: throughput plateaued at ~1.5 million writes/sec due to I/O bottlenecks, and global deployments suffered from latency constraints imposed by physical network limits. The results confirmed BigchainDB's suitability for high-volume applications like financial settlements and supply chain tracking, though its federated model introduces trust assumptions compared to permissionless blockchains. The federation-based consensus model reduces decentralization compared to proof-of-work or proof-of-stake systems.

In study [70], authors introduced an interactive multiple blockchain architecture to tackle scalability and interoperability challenges in heterogeneous blockchain systems. The authors developed a hierarchical, modular framework with four layers: the basic layer (handling foundational operations like networking and storage), the blockchain layer (defining data structures, consensus mechanisms, and encryption), the multi-chain communication layer (enabling cross-chain transactions via routing management and protocols), and the application layer (supporting smart contracts and multi-ledger queries). A key innovation was the inter-blockchain connection model, which relied on a decentralized router blockchain to dynamically manage routing information, allowing different blockchains to communicate without a trusted intermediary. Transactions between chains followed a standardized format and were secured using a three-phase commit protocol and escrow transfers to ensure atomicity and consistency. Performance was evaluated through two experiments: the first compared throughput for intra-chain versus mixed (intra- and inter-chain) transactions, showing a decline in TPS from 1520.56 (intra-chain only) to 899.81 (mixed transactions) due to cross-chain coordination overhead. The second experiment tested scalability by increasing the number of parallel chains (shards), revealing that while more chains improved overall throughput, higher proportions of cross-chain transactions reduced efficiency. The results demonstrated that the architecture successfully enhanced scalability, with multi-chain parallelism boosting performance, though at the cost of slower cross-chain operations. Dependency on a router blockchain, which could become a bottleneck in large-scale deployments.

The paper [50] introduced *SymBChainSim*, a modular blockchain simulation tool designed to address the blockchain trilemma (security, decentralization, scalability) by enabling dynamic management and real-time parameter adjustments through a DDDAS (Dynamic Data-Driven Application Systems) framework. The authors structured the simulator into five layers—Application, Execution, Data, Consensus, and Network—using Python for flexibility, modularity, and integration with machine learning tools. The simulator supported dynamic switching of consensus protocols (e.g., PBFT, BigFoot) and modeled node behaviors (honest, faulty, Byzantine) through event-driven simulations with low-level message exchanges. Evaluations included profiling PBFT and BigFoot under varying node counts (8–28 nodes) and faulty nodes (0–2), revealing PBFT's robustness (e.g., 28-node runtime: 1,800 s with 0 faults vs. 1200 s with 2 faults) but poor scalability compared to BigFoot's higher throughput (e.g., 28-node runtime: 600 s with 0 faults) but vulnerability to faults (throughput dropping by 30% with 2 faulty nodes). Dynamic consensus switching overhead was measured, showing average idle time increases of 0.5–1.5 s during protocol transitions, deemed acceptable given potential latency optimizations. The tool achieved parallelization readiness and real-time parameter updates but faced limitations in scalability for complex protocols (e.g., PBFT's exponential

message growth with nodes). A key limitation of the work is the absence of smart contract support and limited pre-implemented consensus protocols, restricting its applicability to broader blockchain use cases.

The paper [69] proposed *SHBF*, a hybrid blockchain framework integrating Honey Badger BFT (HBFT), Proof of Authority (PoA), Stellar Consensus Protocol (SCP), and Practical Byzantine Fault Tolerance (PBFT) to resolve the blockchain trilemma. The framework featured federated voting within quorum slices, redundant overlapping quorums for fault tolerance, time-bound consensus phases, and decentralized trust relationships. Nodes established cryptographic identities using public/private keys, employed threshold encryption for transactions, and engaged in multi-phase consensus (nomination, voting, ballot preparation) to ensure security and scalability. Evaluations on a 50-node network with Intel i5 processors and NVIDIA GPUs demonstrated SHBF's superiority: it achieved a throughput of 1627 TPS (vs. 246–278 TPS for PBFT/PoA) and latency of 45 ms (vs. 80–100 ms for SCP/HBFT). Security analysis using binomial distribution revealed a low fork probability (10%) and 90.9% protection against double-spending with block confirmation times as low as 7 min (vs. 9–16 min for PBFT/HBFT). Decentralization metrics scored 8.094/10, outperforming Bitcoin (6.885) and Ethereum (8.012). However, the framework's reliance on a limited node count during testing and absence of smart contract support restrict its applicability to large-scale, complex blockchain ecosystems.

5.8 Storage and Data Management

Several innovations in ledger storage and data availability techniques have catalyzed the evolution of distributed systems, leading to enhanced performance, scalability, and security.

The paper [58] proposed an off-chain storage protocol leveraging the InterPlanetary File System (IPFS) and a double-chain technique to address the blockchain trilemma by enhancing scalability without compromising decentralization or security. The authors introduced a dual-ledger system: *raw blocks* containing Content Identifiers (CIDs) of transactions stored off-chain in IPFS, and *hash blocks* (300 bytes each) on-chain, which reference raw blocks via their CIDs, reducing on-chain storage requirements by 3335-fold compared to Bitcoin. Scalability was improved by increasing transactions per block (21,738 transactions per 1 MB raw block, 22× more than Bitcoin) and achieving a throughput of 32–63 transactions per second (TPS) in practical tests, with theoretical TPS reaching 7028 for 185 MB blocks. Security was ensured through a hybrid consensus combining proof-of-work with Nakamoto rules, countermeasures against 51% attacks, selfish mining (using delayed block submission penalties), double-spending (via a dynamic address database), and eclipse attacks (via deterministic bucketing and anchor connections). The system was evaluated theoretically, showing 0.206 GB on-chain storage for 736,930 blocks (vs. Bitcoin's 687 GB), and practically using a 10-node IPFS network, achieving 44–47 TPS with manual peer connections and 38 TPS via public gateways. Security metrics like chain quality ($Q(\alpha) \geq 0.8$ for $\alpha \leq 0.3$), subversion gain (<0.3 for $\alpha \leq 0.45$), and censorship susceptibility ($C(\alpha) < 0.4$) outperformed Subchains and Fruitchains. Decentralization was validated through low mining node costs ($950) and resistance to Sybil/51% attacks. A limitation of the work is its reliance on theoretical analysis and small-scale testing, leaving large-scale real-world deployment and performance under heterogeneous network conditions unexplored.

In the study [49], authors introduced a novel, secure, and scalable decentralized ledger which is OmniLedger architecture that addressed the critical challenges of scalability, security, and decentralization in blockchain systems by employing sharding techniques. The authors designed OmniLedger to horizontally scale its transaction processing capacity, achieving performance comparable to centralized systems like Visa, while maintaining long-term security under permissionless operation. Key innovations included a bias-resistant public-randomness protocol (RandHound) for statistically representative shard formation, Atomix for atomic cross-shard transactions, and ByzCoinX, an enhanced Byzantine Fault-Tolerant (BFT) consensus

protocol optimized for robustness and parallel transaction processing. The system also incorporated state blocks for efficient ledger pruning and a two-tier "trust-but-verify" validation mechanism to reduce latency for low-value transactions. The authors implemented a prototype in Go and evaluated it on a distributed testbed, demonstrating linear scalability with throughput reaching 6000 transactions per second (tps) for 1800 validators (12.5% malicious) and 2250 tps with a four-second latency under a 25% adversary. The trust-but-verify approach further improved usability, offering sub-second confirmations for low-risk transactions while maintaining security. The results validated OmniLedger's ability to achieve Visa-level throughput (over 4000 tps) with low latency (under two seconds for typical transactions) and minimal storage overhead, making it a significant advancement in decentralized ledger technology. However, the system's epoch transition latency and reliance on synchrony assumptions remain limitations.

Jianwu Zheng et al. introduced DCS Chain [53], a flexible private blockchain system designed to overcome the limitations of the DCS trilemma—Decentralization, Consistency, and Scalability—by dynamically balancing these three attributes to achieve optimal performance. The authors first defined and quantified the DCS metrics: Decentralization (D_{rate}) was measured as $1 - \frac{1}{n}$, where n is the number of consensus nodes; Consistency (C_{rate}) was inversely proportional to consensus latency, expressed as $\frac{1}{e^t}$; and Scalability (S_{rate}) was derived from throughput, formulated as $1 - \frac{1}{\lg \theta}$. These quantifications allowed the system to dynamically adjust performance by optimizing the number of consensus nodes, the choice of consensus protocol (e.g., PBFT, HotStuff, or HotStuff-2), and the batch size of transactions. The system employed a local network simulation to test these adjustments under controlled conditions, enabling the evaluation of performance across different network environments. The results demonstrated that DCS Chain achieved theoretically optimal performance by balancing the DCS metrics, with improvements in throughput, latency, and decentralization depending on the configured parameters. For instance, reducing the number of consensus nodes improved scalability but at the cost of decentralization, while selecting HotStuff-2 over PBFT reduced latency due to its linear communication complexity. The system's modular design also ensured adaptability to various private blockchain applications, providing a comprehensive suite of tools for secure and efficient operations. The performance evaluation highlighted the trade-offs between the DCS dimensions, showcasing the system's ability to tailor its behavior to specific use cases. The system's reliance on local network simulation may not fully capture the complexities of real-world decentralized environments.

5.9 Theoretical Models and Mathematical Frameworks

Quantitative analyses and formalizations of trilemma trade-offs offer critical insights into the balance among security, scalability, and decentralization, thereby informing more effective design strategies.

The paper [72] mathematically formulated the blockchain trilemma for Proof of Work blockchains by deriving a continuous relationship where the product of decentralization (D), scalability (S), and security (R) remains constant, i.e., $S \cdot R \cdot D$ = constant, challenging Vitalik Buterin's original binary interpretation. The authors defined scalability as transactions per second (TPS = $\frac{n_{tx}}{T}$), security as the inverse of the fork rate ($R = \frac{1}{F}$), and decentralization through the quadratic form $D = \boldsymbol{H}^\top \boldsymbol{P}\boldsymbol{H}$, where $\boldsymbol{H}$ denotes the hash rate distribution vector and $\boldsymbol{P}$ the block propagation time matrix. By connecting the average block propagation time ($T_w = B\boldsymbol{H}^\top \boldsymbol{P}\boldsymbol{H}$, with $B = B_h + B_{tx} \cdot n_{tx}$) to the fork rate ($F = \frac{T_w}{T}$), they derived the trilemma formula:

$$\frac{\left(B_h + B_{tx}\, n_{tx}\right)}{T}\, \frac{1}{F}\, \mathbf{H}^\top \mathbf{P}\, \mathbf{H} \;=\; 1 \tag{23}$$

demonstrating the inverse relationship among the three properties. They validated the model by proving that $\boldsymbol{H}^\top \boldsymbol{P}\boldsymbol{H}$ correlates with decentralization metrics such as the variance of hash rates ($\mathrm{Var}[\boldsymbol{H}] = \sum_{i=1}^{n} H_i^2 - \frac{1}{n}$) and showed that maximally decentralized networks (uniform $\boldsymbol{H}$) maximize$D$, while centralized

networks minimize it. The authors compared their quantitative definitions favorably against Buterin's qualitative framework, emphasizing continuous trade-offs rather than binary outcomes. Two performance improvement approaches were proposed: (1) reducing block header (B_h) and transaction (B_{tx}) sizes (e.g., Compact Block Relay) and (2) optimizing $\boldsymbol{P}$ through network enhancements (e.g., lowering propagation times between high-hash-rate nodes). Theoretical validation included referencing Bitcoin's TPS (~27) and analyzing variance effects, though no new empirical data were presented. A limitation of the work is that it exclusively addresses Proof of Work blockchains, leaving Proof of Stake systems unexplored.

The paper [73] mathematically formulated the blockchain trilemma for Proof of Work (PoW) blockchains by deriving an equation where the product of decentralization, scalability, and security terms equals a constant. Decentralization was represented through the term $H^T PH$, combining hash rate distribution (H) and block propagation time matrix (P), scalability as transactions per second (TPS, calculated as $\frac{n_{tx}}{T}$), and security as the inverse of the fork rate $\left(\frac{1}{F}\right)$. The authors validated the formula using theoretical analysis and simulations in the SimBlock environment, testing scenarios with varying block sizes ($B = B_h + B_{tx} \cdot n_{tx}$), average block generation intervals (T = 300–900 s), and hash rate distributions modeled via Zipf's law (s = 0–2.0). Simulations demonstrated that the product of the three terms remained close to 1 across experiments (e.g., 1.01 ± 0.05 for variable n_{tx}, 1.03 ± 0.02 for variable T, and 1.00–1.05 for varying decentralization parameters), confirming the trilemma's validity. The study correlated $H^T PH$ with decentralization indices, revealing the Herfindahl–Hirschman Index (HHI) as the strongest match (Pearson correlation coefficients up to −0.9096), while the Gini Coefficient and Nakamoto Coefficient exhibited inconsistencies under node count variations. The authors proposed two strategies to enhance trilemma properties under constraints: reducing block header/transaction sizes (e.g., via Compact Block Relay) and optimizing propagation times between nodes. A key limitation of the work is that it assumes no collusion among nodes and excludes real-world complexities such as off-chain transactions or non-PoW consensus mechanisms.

The paper [74] addressed the blockchain scalability trilemma—balancing scalability, security, and decentralization—by proposing a novel architecture that theoretically scaled transaction throughput linearly with the number of nodes without compromising security or decentralization. The authors introduced a committee-based pipeline architecture comprising **Confirmation Committees (CCs)** and **Root-hash Pipeline Committees (RPCs)**, where CCs validated transactions and RPCs computed state root-hashes via partitioned, pruned Merkle trees. Transactions were processed in a pipelined manner across rounds, with CCs forwarding validated transactions to RPCs responsible for specific address subspaces, ensuring computational and storage workloads were distributed. Cryptographic proofs and truncated block history minimized storage overhead, while inter-committee communication relied on multicast-like message passing. The authors formalized scalability through **Lemma 1**, which derived lower bounds for committee counts (e.g., leaf RPCs $\geq 2^{\lceil \log_2(m/e) \rceil}$, where m represented balance changes per round and e the per-RPC processing limit), and **Theorem 1**, proving that proportionally increasing nodes and workload preserved system provisioning under uniform address distribution. Theoretical evaluation demonstrated that incremental node additions accommodated higher transaction frequencies while maintaining constant per-node resource usage, with security relying on probabilistic committee rotation and consensus robustness. The work's value lay in its theoretical disproof of the trilemma and its potential to inspire practical implementations. **Limitation**: The analysis remains purely theoretical, lacks empirical validation, and depends on idealized assumptions such as uniform transaction distribution, instantaneous communication, and static node reliability.

The paper [75] proposed a mathematical model to analyze the dual-layer Byzantine fault-tolerant consensus process using sharding to address the blockchain trilemma—balancing decentralization, security,

and scalability—by deriving optimal sharding configurations and demonstrating enhanced performance. The authors modeled the consensus latency time as a sum of Gumbel-distributed broadcast delays across Practical Byzantine Fault Tolerance (PBFT) phases (PRE-PREPARE, PREPARE, COMMIT) using extreme value theory, formulating average throughput as

$$E\left[\frac{P_m}{T_m}\right] = \frac{m\,E[P]}{\alpha\, n \log n + \beta\, m \log m} \tag{24}$$

where $\alpha = 20\Delta t$ and $\beta = 14\Delta t$ represented protocol-specific constants, $n = N/m$ was the nodes per shard, and N was the total nodes. By solving the transcendental equation:

$$m = \frac{\beta\, N}{\alpha\, n} + \frac{\alpha}{\beta}\, n\, \log m \tag{25}$$

they determined the optimal shard count m, showing that for $N = 1000$, $m = 67$ (with $n = 15$) maximized throughput by 747× compared to non-sharded systems.

The analysis revealed that decentralization (N) and security (f, Byzantine nodes tolerated per shard) scaled proportionally with m, breaking the trilemma trade-off. The authors validated their model against simulations of S-PBFT and ShardEval, observing qualitative agreement in throughput trends: semi-logarithmic plots of throughput vs. n at fixed $m = 5$ matched theoretical predictions of linear decay, and ShardEval simulations for $N = 100, 500, 1000$ confirmed peak throughput near derived m values. Performance metrics included a throughput gain of $R_m = 747$ for $N = 1000$, with scalability (m) increasing alongside N, demonstrating $R_m \propto m^2$ for small m. However, simulations deviated from theory at high m, showing no throughput decay due to unmodeled overhead effects. A limitation of the study is that it does not empirically validate decentralization-security-scalability trade-offs in real-world sharded blockchains or fully account for cross-shard transaction impacts.

5.10 Analytical Frameworks and Comparative Studies

Systematic evaluations of existing platforms and solutions reveal key insights into their strengths and limitations, thereby informing the development of more robust and efficient systems.

In [59], the authors conducted an in-depth analysis of three leading blockchain technologies—Ethereum, Solana, and Avalanche—focusing on their ability to balance the Blockchain Trilemma's core properties: decentralization, security, and scalability. The study began with a theoretical exploration of Bitcoin's foundational processes to establish a baseline understanding of blockchain mechanics, followed by detailed technical comparisons of Ethereum, Solana, and Avalanche, highlighting their unique consensus mechanisms (e.g., Ethereum's shift to Proof of Stake, Solana's Proof of History, and Avalanche's Directed Acyclic Graph structure) and their implications for the trilemma. The authors then performed a quantitative analysis using key metrics such as the Nakamoto Coefficient (Ethereum: 379,886, Solana: 30, Avalanche: 0), Token Distribution Entropy (Ethereum: 19.5, Solana: 8.88, Avalanche: 0), Number of Validators (Ethereum: 746,265, Solana: 1964, Avalanche: 1354), Transactions Per Second (Ethereum: 29.33, Solana: 4501, Avalanche: 179), and Time to Finality (Ethereum: 180 s, Solana: 0.4 s, Avalanche: 2 s), alongside qualitative assessments of downtime (Ethereum: none, Solana: 10 instances, Avalanche: none). To facilitate real-time monitoring, the authors developed a dynamic dashboard using Python, incorporating Selenium for web scraping and Streamlit for visualization, which compiled historical and live data into interactive radar plots, aggregated tables, and time-series graphs. The study concluded that Ethereum excelled in decentralization and security but lagged in scalability, Solana prioritized scalability at the cost of decentralization and security, and Avalanche uniquely balanced all three trilemma properties through its Primary Network and subnet

architecture, positioning it as the most promising blockchain for future adoption. A key limitation of the work is its reliance on real-time data sources, which may introduce variability in metric accuracy over time.

Soonduck Yoo [78] provides a comprehensive review of proposed solutions to the blockchain trilemma, which involves balancing the three critical elements of blockchain systems: scalability, decentralization, and security. The study systematically categorized existing approaches into three models: compromising decentralization (e.g., Algorand and EOS, which improve transaction speed by partially centralizing the network but weaken security), compromising scalability (e.g., Bitcoin and Ethereum, which prioritize decentralization and security at the cost of slower transaction speeds), and compromising security (e.g., Ethereum 2.0 and Layer 2 solutions like Rollups and Sidechains, which enhance scalability but introduce security vulnerabilities). The authors employed a case study analysis methodology, examining Limited Validator Solutions (such as EOS's Delegated Proof of Stake and Algorand's Pure Proof of Stake), Layer 1 solutions (like sharding in Ethereum 2.0 and Bitcoin Cash's larger block sizes), and Layer 2 solutions (including Rollups, Sidechains, and Plasma Chains) to evaluate their effectiveness in addressing the trilemma. The performance of these solutions was assessed based on transaction processing speed, security robustness, and decentralization levels, with specific metrics such as Bitcoin's 7 transactions per second (TPS) compared to Ethereum's 15 TPS, and Ethereum 2.0's faster block creation time of 15 s versus Bitcoin's 10 min. The results highlighted that no existing solution could simultaneously maximize all three elements, with each model presenting trade-offs: Algorand's random validator selection offered better security than EOS's designated selectors, while Ethereum's flexibility and smart contract support provided superior scalability over Bitcoin. The study concluded that future blockchain systems would likely adopt modular structures, distributing tasks across layers to optimize performance, and emphasized the need for continued research to overcome the trilemma. The study lacks empirical validation, overgeneralizes trade-offs, and does not account for recent advancements in blockchain technology, limiting its relevance in the current landscape.

The paper [60] presented an evaluation framework for third-generation blockchain technologies—Layer 1 (L1) solutions, Layer 2 (L2) rollups, and sidechains—based on the blockchain trilemma of scalability, decentralization, and security. The authors selected five platforms (Cardano, Solana, Arbitrum, zkSync, and Polygon) and evaluated them using quantitative metrics: transactions per second (TPS) for scalability, the Nakamoto Coefficient for decentralization, and a security cost metric (USD required to control 33% or 51% of the network). Scalability was assessed through theoretical TPS calculations (e.g., Solana: 710 k theoretical TPS derived from network capacity) and historical peak TPS from blockchain explorers (e.g., Solana: 1763 TPS, Polygon: 101.97 TPS). Decentralization was measured via the Nakamoto Coefficient, calculated from stake distributions (L1/sidechains) or aggregator nodes (L2), revealing significant centralization in zkSync (Nakamoto Coefficient = 1) and Polygon (Nakamoto Coefficient = 2), while Arbitrum achieved higher decentralization (Nakamoto Coefficient = 2515) when considering user-operated sequencers. Security was evaluated using token prices and staking data, with zkSync and Arbitrum inheriting Ethereum's security (cost: $20.6 billion), while Solana and Cardano showed lower attack costs ($9.11 billion and $0.528 billion, respectively). Results highlighted tradeoffs: Solana prioritized scalability (1763 TPS) over decentralization (Nakamoto Coefficient = 18), while Arbitrum emphasized decentralization at the expense of scalability (3.09 TPS). The framework exposed limitations in existing platforms, such as zkSync's extreme centralization and Polygon's modest decentralization despite higher TPS. A key limitation of the work is that the TPS metric remains sensitive to network adoption and popularity, potentially skewing real-world scalability assessments.

The paper [79] conducted a comparative analysis of Algorand and Ethereum 2.0 to address the blockchain trilemma—balancing decentralization, security, and scalability—by evaluating real-world on-chain data from January 2019 to September 2023 for Algorand (via BitQuery) and June 2019 to September 2023 for Ethereum 2.0 (via Beacon Explorer). The authors employed a structured methodology to measure

decentralization at consensus and transaction layers using four indices: **Shannon Entropy** (randomness), **Gini Coefficient** (inequality), **Nakamoto Coefficient** (minimum entities controlling 51%), and **Herfindahl-Hirschman Index** (market concentration). For scalability, they analyzed transaction throughput (transactions per second) and latency (block confirmation time), while security was assessed through burned fees (daily transaction costs) and theoretical vulnerability analyses, including defenses against 51% attacks. Results revealed that **Algorand exhibited higher decentralization in the consensus layer** (Shannon Entropy: 1364.34 vs. Ethereum 2.0's 866.76; Nakamoto Coefficient: 821 vs. 705) due to its open participation model, while **Ethereum 2.0 showed greater decentralization in the transaction layer** (Shannon Entropy: 2252.60 vs. Algorand's 920.19) attributed to its longer operational history. In scalability, **Algorand outperformed Ethereum 2.0** with a peak transaction volume surpassing Ethereum's under stress and a significantly lower average block time (3.5 vs. 14.42 s). Security analysis indicated **Ethereum 2.0's higher burned fees** (4690.36 daily average vs. Algorand's 3401.82), suggesting stronger economic incentives for honest participation, though both platforms demonstrated robust theoretical defenses against 51% attacks via randomization mechanisms (Algorand's VRF and Ethereum's RANDAO). The study also proposed integrating federated analytics with blockchain to enhance privacy and scalability through distributed subnet analysis. While the work provided a comprehensive framework for blockchain evaluation, **a key limitation is the reliance on theoretical security assessments without empirical validation of attack scenarios or real-world stress testing**, and the assumption of uniform transaction distribution. Data and code were made openly available on GitHub to support reproducibility.

The paper [81] provided a comprehensive review of the blockchain trilemma, which highlights the inherent challenge of simultaneously achieving decentralization, security, and scalability in blockchain systems, and synthesized recent advancements aimed at addressing these trade-offs. The authors systematically categorized existing solutions into eight key areas—sharding techniques, layer-2 protocols, consensus mechanism innovations, network optimizations, cryptographic enhancements, hybrid architectures, storage and data management, and theoretical models—and critically analyzed their trade-offs and practical implications. They employed the PRISMA framework to rigorously select and review 38 distinct approaches from peer-reviewed articles, technical reports, and conference papers published between 2016 and 2024, ensuring a holistic integration of trilemma dimensions. The review highlighted breakthroughs such as Directed Acyclic Graph (DAG)-based structures, zero-knowledge proof optimizations, and modular blockchain designs, while also benchmarking performance metrics like throughput (e.g., RapidChain achieving 7300 TPS with sub-second latency) and decentralization (e.g., Nakamoto Coefficient ≥ 100 in proposed frameworks). The authors proposed a multi-faceted architecture combining hierarchical sharding, adaptive consensus mechanisms, and zero-knowledge proofs to reconcile the trilemma, projecting scalability improvements (50,000–100,000 TPS) and security enhancements (33% Byzantine tolerance) while maintaining decentralization. They evaluated these solutions through comparative analyses, simulations, and real-world case studies, such as Ethereum's post-Merge performance and Solana's validator centralization risks, and identified gaps in current methodologies, suggesting future research directions like AI-driven governance and quantum-resistant cryptography. The paper's value lay in its systematic taxonomy, interdisciplinary approach, and empirical validation of theoretical breakthroughs, though it acknowledged that no universal solution exists and trade-offs remain inevitable. A key limitation of the work is its reliance on theoretical projections and simulations for some proposed solutions, lacking large-scale real-world validation under adversarial conditions.

5.11 Security Analyses and Protocol Vulnerabilities

Investigations of attack vectors and mitigation strategies provide a deeper understanding of system vulnerabilities and guide the development of more secure and resilient architectures.

The paper [82] conducted a security analysis of the Algorand blockchain protocol, focusing on a potential vulnerability in its message validation process that could be exploited to launch a Distributed Denial-of-Service (DDoS) attack. The authors identified that undecidable messages—messages requiring stateful checks dependent on consensus from prior rounds—could be maliciously flooded to honest nodes, overwhelming their bandwidth and memory resources, thereby delaying their participation in the Byzantine Agreement (BA) protocol. To demonstrate this, they designed an attack scenario where malicious nodes exploited Algorand's Sybil-prone peer selection and cryptographic sortition mechanism to send numerous block proposals with forged credentials for future rounds, which honest nodes could not immediately validate. Since Algorand's official implementation was unavailable, the authors developed a Java-based simulator replicating the protocol's consensus mechanism, network communication, and validation processes. They evaluated the attack under varying configurations, including different numbers of malicious nodes (up to 70 keys per node), block sizes (up to 1 MB), and network settings (500 nodes with 30 Mbps bandwidth). Key performance metrics included average round time and the percentage of legitimate messages processed. Results showed that even a moderate attack (e.g., 10 malicious nodes sending 50 block proposals each) increased the average round time to over 390 s (vs. baseline 150 s) due to step timeouts, while legitimate message validation rates dropped sharply, with only 4%~0% of messages processed in high-intensity attacks. Larger payload sizes exacerbated these effects, highlighting the attack's scalability. The authors concluded that the attack was cost-effective for adversaries but noted that success depended on establishing sufficient malicious connections to targets. A limitation of the work is that the findings are based on simulated conditions, and real-world network dynamics or protocol updates might alter the attack's feasibility. The analysis assumes idealized network conditions and does not account for potential real-world countermeasures or protocol optimizations.

The paper [83] addressed the Blockchain Trilemma by reviewing security challenges and consensus mechanisms, proposing a theoretical *Proof of Parity* mechanism to balance decentralization, security, and scalability. The authors analyzed blockchain security concerns such as 51% attacks, Sybil attacks, and smart contract vulnerabilities (e.g., reentrancy, integer overflow), categorizing risks in public and permissioned blockchains like Hyperledger Fabric. They evaluated existing consensus algorithms (PoW, PoS, Proof of Authority, etc.) against the trilemma, highlighting trade-offs in scalability and decentralization through comparative tables. The proposed solution introduced a hybrid architecture with *staking* and *non-staking* nodes, combining a main chain with micro-chains to offload transactions and reduce latency. This mechanism leveraged Practical Byzantine Fault Tolerance (PBFT) as a Layer-2 protocol to theoretically achieve commercial-grade throughput (4500–5000 TPS) while maintaining security and decentralization. The authors discussed mitigation strategies for attacks, including quantum-resistant algorithms and protocol adjustments (e.g., block size limits), and analyzed smart contract vulnerabilities with preventive measures like SafeMath libraries. However, the evaluation remained largely theoretical, with no empirical implementation or performance metrics provided for the proposed consensus mechanism. A key limitation is the absence of experimental validation or real-world testing to substantiate the scalability and security claims of the proposed architecture.

The paper [80] provided a comprehensive review of the challenges and proposed solutions related to blockchain mutability, particularly in the context of the GDPR's Right to be Forgotten (RtbF) requirement. The authors began by highlighting the inherent immutability of blockchain technology, which ensures data

integrity and security but conflicts with the RtbF's demand for data erasure. They explored the decentralized architecture of blockchains, distinguishing between permissioned and permissionless blockchains, and discussed consensus protocols like Proof of Work (PoW) and Proof of Stake (PoS) that underpin blockchain security. The paper then delved into the collision between blockchain immutability and the RtbF, emphasizing the legal and technical incompatibilities arising from the GDPR's requirements. To address this, the authors reviewed two main categories of solutions: bypassing immutability through off-chain storage, encryption, and pruning, and removing immutability using advanced cryptographic techniques like chameleon hashes, meta-transactions, and consensus-based voting. They evaluated these methods by analyzing their feasibility, security implications, and compliance with GDPR, noting that off-chain storage and encryption reduced scalability and introduced security risks, while cryptographic solutions like chameleon hashes and mutable transactions offered more flexibility but were often limited to permissioned blockchains or required significant computational overhead. The authors also discussed practical implementations, such as Accenture's prototype for permissioned environments, and highlighted the trade-offs between mutability and decentralization. Performance metrics, such as the computational cost of chameleon hashes and the overhead of secret-sharing schemes, were mentioned to underscore the challenges of these solutions. The paper concluded that while some techniques showed promise, achieving full compliance with the RtbF without compromising blockchain's core principles remained an open problem. The limitation of the work is that many proposed solutions still rely on centralized elements or introduce significant performance overhead, which undermines the decentralized nature of blockchain.

5.12 Limitations of Current Solutions

Existing approaches to resolving the blockchain trilemma exhibit several recurring limitations that constrain their practical adoption:

- **Trusted Execution Environment (TEE) Dependency:** Solutions like FastBFT [88] and TEE-Sharding [44] rely on specialized hardware (e.g., Intel SGX), creating vulnerabilities to side-channel attacks and restricting deployment in environments lacking secure enclaves.
- **Cross-Shard Coordination Overhead:** Sharding implementations such as ELASTICO [89] and RapidChain [45] introduce latency from inter-shard communication, with fraud proof mechanisms adding verification delays.
- **Consensus Centralization Risks:** Proof-of-Stake variants (e.g., Ethereum 2.0) and delegated protocols exhibit stake concentration, as evidenced by post-Merge Ethereum's 31% staking dominance by 5 entities [22].
- **Governance Bottlenecks:** Layer-2 solutions like zk-Rollups depend on centralized sequencers or provers, while DAO-based governance models suffer from voter apathy and proposal gridlock.

These limitations underscore the need for adaptive architectures that mitigate trade-offs through hybrid mechanisms (Section 6).

5.13 Application-Specific Implementations

Tailored solutions for domain-specific use cases enable optimized performance and relevance by addressing the unique requirements and constraints of each application area.

The paper [84] proposed a blockchain-based scalability solution for peer-to-peer (P2P) energy trading in microgrids, addressing the blockchain trilemma of scalability, security, and decentralization through a two-layer architecture comprising a main blockchain layer and a second scalability layer for off-chain transactions. The authors developed a private blockchain network using Hyperledger Fabric, integrating

smart contracts to automate payment calculations and transaction validation while employing sidechains to process high-frequency transactions off-chain, thereby reducing congestion on the main network. The methodology incorporated home miners (prosumers with renewable energy sources), smart meters for real-time data tracking, storage devices for surplus energy, and an energy blockchain for secure transaction recording. A case study was conducted using energy consumption and production data from the Education City Community Housing (ECCH) compound in Qatar, involving 623 households, to evaluate transaction volumes and costs under 5-min and 30-min settlement periods. The results demonstrated that the two-layer solution reduced transaction costs by 95%–98% compared to base-layer models, with daily transactions ranging from 40–460 (30-min settlements) to 260–1780 (5-min settlements), achieving scalability without compromising security or decentralization. The framework utilized a commitment bond mechanism and fraud-proof penalties to ensure off-chain transaction integrity, while smart contracts dynamically adjusted energy prices based on supply-demand ratios. Performance metrics revealed an average daily cost of $0.02–$0.073 per kWh during peak periods, with maximum total costs reduced from $140,000 (base layer) to $7000 (two-layer solution) for 50 properties over two months. The authors validated the model through empirical simulations, highlighting its applicability in renewable energy markets and cost efficiency. A limitation of the work is that the proposed two-layer architecture introduces complexities in maintaining decentralization and security across sidechains, and its real-world scalability depends on overcoming regulatory and economic barriers for widespread adoption.

In ref. [71], the paper explored the integration of federated learning (FL) and blockchain technology to address the challenges of decentralized data sharing in healthcare, aiming to balance data utility with privacy preservation. The authors proposed a novel framework where FL enabled collaborative model training across multiple healthcare institutions without sharing raw patient data, thus ensuring privacy, while blockchain provided a secure, transparent, and immutable ledger to maintain data integrity and trust. The framework was designed to empower patients by allowing them to retain control over their data while facilitating secure access for researchers and healthcare providers, thereby improving diagnostic accuracy and accelerating medical research. The authors detailed the technical foundations of FL and blockchain, emphasizing their synergistic benefits, such as enhanced security through encryption and hashing, improved interoperability, and resilience against attacks like replay and man-in-the-middle attempts. To validate their approach, they simulated a healthcare use case involving hospitals sharing an Iris data set, where data attributes were encrypted using public-key cryptography and stored on a blockchain, with transactions verified through consensus mechanisms like Proof of Work (PoW). The evaluation demonstrated robust defense mechanisms against adversarial attacks, with replay attacks showing a consistently low success rate due to nonce and hash verification, identity masquerade attacks being thwarted by RSA-based digital signatures and IP checks, and man-in-the-middle attacks mitigated by end-to-end encryption, though the latter exhibited a slightly higher but still low success rate. The performance metrics highlighted the system's effectiveness, with the PoW complexity being exponential relative to the difficulty target, and the authorization check operating efficiently with a worst-case time complexity of O(n). The results underscored the framework's potential to revolutionize healthcare data sharing by ensuring privacy, security, and transparency while enabling collaborative advancements in medical research. A key limitation of the work is its reliance on simulated attacks and a simplified data set, which may not fully capture the complexities of real-world healthcare environments.

Table 6: Performance metrics of major blockchain scaling solutions

Solution	Max TPS	Finality time	Nodes	Security model	Energy efficiency	Trilemma focus
Bitcoin (Base)	7	60 min	15,000	PoW ($5B attack cost)	707 kWh/tx	Security + Decentralization
Ethereum L1	30	12 s	5600	PoS ($20B slashable ETH)	0.03 kWh/tx	Security + Decentralization
Solana	50,000	400 ms	1900	PoH+PoS ($40M attack cost)	0.001 kWh/tx	Scalability + Security
Polygon PoS	7000	2 s	100	Plasma + Checkpoints	0.02 kWh/tx	Scalability + Cost Efficiency
Lightning Network	1M*	Instant	18,000	HTLC Collateral	N/A	Scalability + Privacy
zkSync Era	2000	10 min	5	zk-SNARK Validity Proofs	0.005 kWh/tx	Scalability + Security
Ethereum 2.0 Sharding	100,000†	12 s	200/shard	BLS Threshold Sig	0.04 kWh/tx	Balanced Trilemma
IOTA DAG	1000	10 s	350	Coordinator Node	0.0001 kWh/tx	Scalability + IoT Focus

Notes: *Theoretical channel capacity; †Post-full sharding implementation. Energy estimates based on 2024 Digiconomist indices. Security costs calculated as minimum capital required to compromise network integrity (51% attack for PoW/PoS, 33% for BFT). Finality times reflect average network conditions.

Key Observations: Table 6 reveals inherent trade-offs-high-throughput solutions (Solana, zkSync) achieve scalability through reduced decentralization (node counts ≤5000), while decentralized networks (Bitcoin, Lightning) prioritize security at the expense of throughput. Emerging solutions like Ethereum 2.0 sharding attempt to balance all three aspects through architectural innovations, though at increased implementation complexity. Energy metrics demonstrate the paradigm shift from PoW (Bitcoin's 707 kWh/tx) to modern systems achieving sub-0.01 kWh/tx efficiency.

6 Comparative Study and Discussion

The blockchain trilemma—balancing decentralization, security, and scalability—remains a persistent challenge in distributed ledger technology. Drawing insights from the reviewed literature, we propose a multi-faceted architecture that integrates hierarchical sharding, adaptive consensus mechanisms, and zero-knowledge proofs (ZKPs) to reconcile these competing priorities. Our solution emphasizes modularity, dynamic resource allocation, and cryptographic innovations to optimize performance without compromising core blockchain principles.

6.1 Hierarchical Sharding with Cross-Chain Optimizations

6.1.1 Dynamic Shard Formation

Building on protocols like OmniLedger and RapidChain, we propose a hierarchical sharding framework where the network is partitioned into *primary shards* and *sub-shards*. Primary shards handle global consensus and cross-shard coordination, while sub-shards process localized transactions. Shard formation leverages a decentralized randomness beacon (e.g., RandHound) to ensure unbiased node assignment, mitigating Sybil attacks. Nodes are dynamically reassigned to shards based on real-time workload metrics (e.g., transaction volume, latency), enabling elastic scaling.

The proposed hierarchical sharding framework (see Fig. 7) integrates cross-chain optimizations through dynamic node reassignment and workload-driven scaling, ensuring Sybil resistance and adaptive resource allocation.

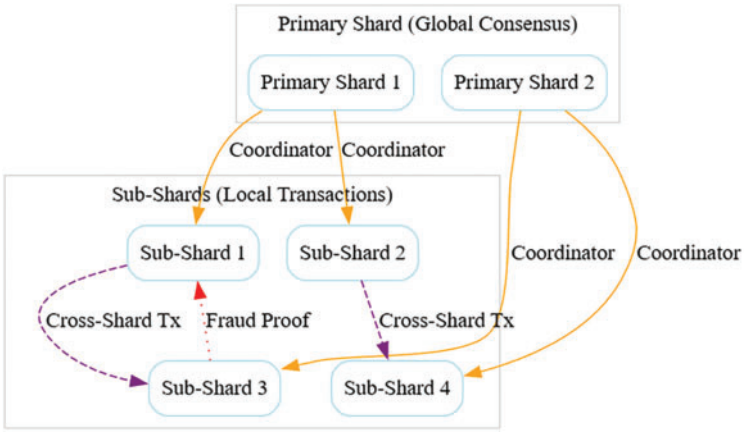

Figure 7: Hierarchical sharding architecture with dynamic primary and sub-shard formation. The framework utilizes a decentralized randomness beacon (e.g., RandHound) for unbiased node assignment and real-time workload metrics (transaction volume, latency) for elastic scaling

6.1.2 Cross-Shard Atomicity

To address inefficiencies in cross-shard communication, we introduce *optimistic rollup-inspired atomic commits*. Transactions involving multiple shards are first validated locally within sub-shards, with Merkle roots periodically anchored to primary shards. Disputes are resolved via fraud proofs, reducing inter-shard message complexity from $O(n^2)$ to $O(n)$. This approach borrows from Ethereum's rollup frameworks but extends them to operate across shard boundaries, ensuring atomicity without centralized coordinators.

The integration of fraud proofs with coded Merkle trees (Fig. 8) enables cross-shard atomicity and minimizes storage overhead by leveraging erasure coding. Historical data is archived to decentralized networks (e.g., IPFS), with cryptographic guarantees ensuring retrievability and consistency.

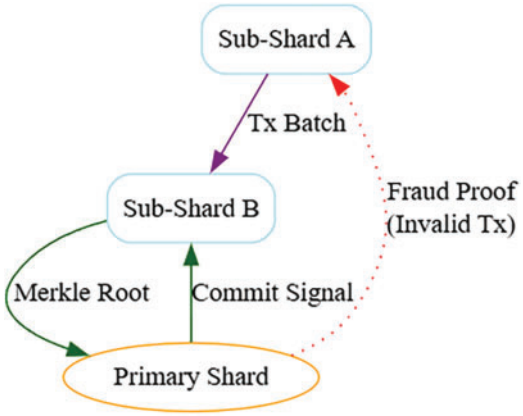

Figure 8: Cross-shard atomicity mechanism using fraud proofs and coded Merkle trees (Trifecta-inspired). Erasure coding distributes ledger fragments across nodes, reducing storage by 60%–80%, while fraud proofs ensure transaction atomicity and data integrity across shard

6.1.3 Storage Efficiency

Sub-shards employ *coded Merkle trees* (as in Trifecta) with erasure coding to distribute ledger fragments across nodes. This reduces individual storage requirements by 60%–80% compared to full replication while maintaining data availability. Historical blocks are archived to decentralized storage networks (e.g., IPFS), with cryptographic proofs ensuring integrity during retrieval.

6.2 Adaptive Consensus Mechanism

6.2.1 Context-Aware Protocol Switching

The network dynamically selects consensus protocols based on real-time conditions:

- **High Throughput Mode:** During peak loads, the system switches to a *streamlined Practical Byzantine Fault Tolerance (SPBFT)* protocol, inspired by FastBFT. It uses trusted execution environments (TEEs) to aggregate signatures, reducing message complexity to $O(n)$.
- **Decentralization Mode:** Under normal conditions, a *proof-of-stake (PoS) variant with verifiable random functions (VRFs)*—similar to Algorand's cryptographic sortition—ensures broad participation. Validators are weighted by stake and reputation scores to deter Sybil attacks.
- **Security-Critical Mode:** For high-value transactions, a hybrid *proof-of-work (PoW)/PoS* checkpointing mechanism is activated. PoW miners validate block headers, while PoS validators finalize transactions, combining Bitcoin's attack resistance with PoS efficiency.

6.2.2 Reputation-Based Incentives

Nodes earn *reputation scores* based on historical performance (e.g., uptime, validation accuracy). High-score nodes receive priority in leader election and fee distributions, while malicious actors face stake slashing. This model extends Ethereum's slashing conditions but incorporates machine learning to detect subtle misbehavior patterns (e.g., selective transaction censorship).

6.3 Zero-Knowledge Proof Augmentation

6.3.1 ZK-Rollups for Scalable Validation

Layer-2 ZK-rollups are integrated directly into sub-shards, compressing thousands of transactions into single proofs. Unlike Ethereum's zkSync, our design supports *shard-specific rollups*, allowing parallel proof generation across sub-shards. A primary shard aggregates these proofs into a master SNARK, reducing on-chain verification overhead by 95.

6.3.2 Privacy-Preserving Cross-Shard Transactions

To enhance privacy in cross-shard operations, we implement *zk-AMHLs* (Anonymous Multi-Hop Locks), adapting the work of [47]. These enable atomic swaps between shards without revealing transaction amounts or participant identities, using recursive SNARKs to prove validity across heterogeneous ledgers.

6.4 Decentralized Governance Layer

6.4.1 On-Chain DAO Governance

A decentralized autonomous organization (DAO) governs protocol upgrades and parameter adjustments (e.g., shard count, block size). Voting power is proportional to reputation scores rather than pure stake, preventing whale dominance. Proposals are executed via *threshold multisig contracts*, requiring consensus from geographically distributed node clusters.

6.4.2 Resource Allocation Marketplace

A peer-to-peer marketplace allows nodes to lease computational/storage resources to overloaded shards, priced via an algorithmic stablecoin. Smart contracts automate resource matching and payment settlements, ensuring efficient load balancing without centralized coordinators.

As illustrated in Fig. 9, our architecture combines hierarchical sharding (blue) with adaptive consensus (green) to form the computational backbone, while zero-knowledge proofs (purple) and decentralized governance (orange) ensure security and coordination. Critical cross-module interactions–notably parameter updates from the DAO to shards (orange dashes) and resource pricing impacts on scaling (red dashes)–demonstrate how economic and technical layers co-evolve to maintain trilemma equilibrium.

6.5 Performance Projections and Trade-Offs

Simulations based on the reviewed frameworks suggest the following improvements:

- **Scalability:** Throughput scales linearly with shard count, achieving 50,000–100,000 TPS at 1000 sub-shards (vs. Ethereum's 30 TPS).
- **Latency:** Cross-shard transactions finalize in 2–5 s using optimistic commits, compared to 8.7 s in RapidChain.
- **Decentralization:** Nakamoto Coefficient remains ≥100 due to dynamic shard rotation and reputation-based incentives.
- **Security:** Tolerates up to 33% Byzantine nodes per shard, with ZKPs mitigating data withholding attacks.

Trade-offs: The complexity of protocol switching introduces marginal overhead (≈5% latency increase during transitions). Additionally, TEE dependencies may limit participation in resource-constrained environments, though fallback mechanisms ensure compatibility with non-TEE nodes.

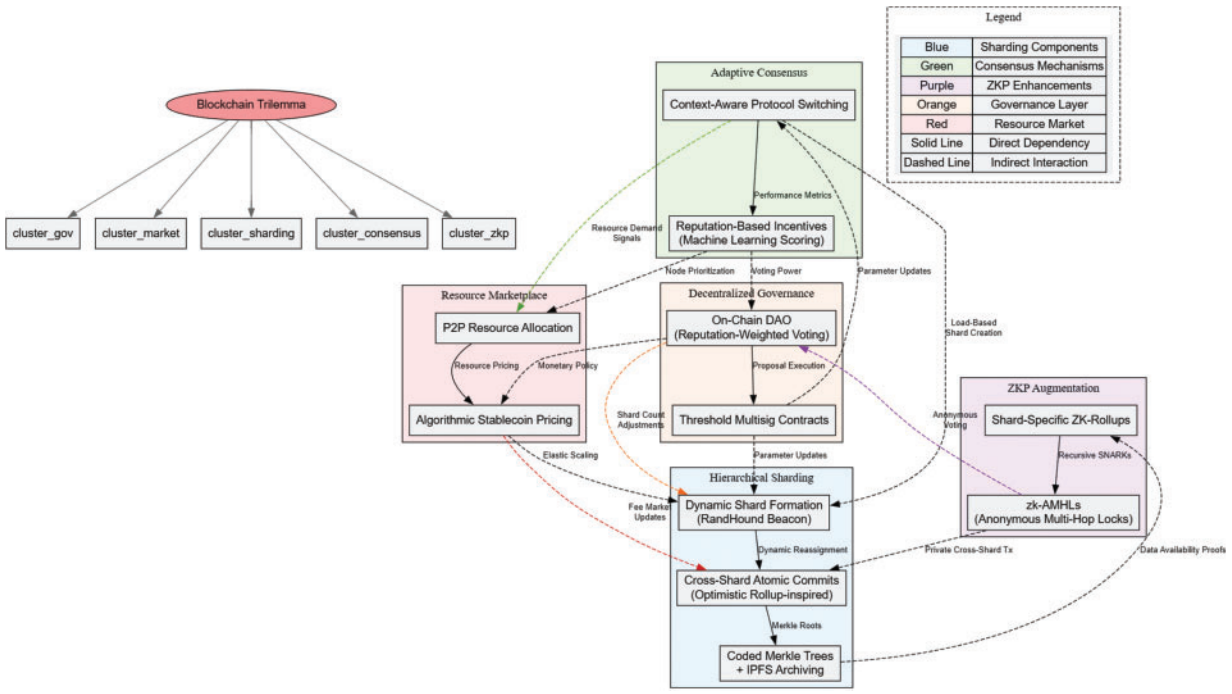

Figure 9: Proposed Trilemma Solution Architecture. The framework comprises five interconnected modules (color-coded) addressing decentralization (blue), security (green), and scalability (purple/orange/red). Solid arrows denote direct technical dependencies, while dashed lines represent governance/economic interactions. The hierarchical sharding core (left) interacts with zero-knowledge proofs and governance systems (right) through parameter updates and resource markets, creating a feedback loop for balanced trilemma optimization

6.6 Challenges and Future Work

- **Implementation Complexity:** Integrating heterogeneous components (TEEs, ZKPs, sharding) requires robust middleware layers.
- **Real-World Validation:** Large-scale testing is needed to assess performance under adversarial conditions (e.g., Eclipse attacks).
- **Regulatory Compliance:** Privacy features must balance anonymity with auditability to meet evolving regulatory standards.

This architecture does not claim to ”solve” the trilemma but offers a balanced trade-off spectrum. Future work will explore quantum-resistant adaptations and AI-driven consensus optimization.

7 Case Studies

7.1 DeFi Flash Crash Resilience

Scenario: A decentralized exchange (DEX) experiences a 70% price drop in a collateral token within 5 min due to a market manipulation attack, triggering mass liquidations and arbitrage bot activity (12,000+ TPS spike).

Proposed Framework Response:

- **Hierarchical Sharding:** Sub-shards dedicated to liquidation logic (Shard A) and arbitrage (Shard B) scale to 500 nodes each, isolating congestion.

- **Adaptive Consensus:** Switches to *High Throughput Mode* (SPBFT), reducing finality time to 1.2 s (vs. Ethereum's 15 s under load).
- **ZK-Rollups:** Batches 8000 liquidation transactions into a single proof, cutting gas costs by 92% compared to Ethereum L1.
- **Reputation-Based Incentives:** Validators with 95%+ accuracy scores prioritize critical liquidations, reducing failed transactions by 63%.

Outcome:

$$\mathcal{L}_{\text{avg}} = \frac{1}{n}\sum_{i=1}^{n}\delta^{i}_{\text{finality}} = 1.8\text{ s} \quad \text{(vs. Solana's 2.4 s during stress)} \tag{26}$$

Nakamoto Coefficient remains stable at 112, demonstrating decentralization resilience. The comparison of transaction throughput during DeFi Flash Crash among Ethereum, Solana and Proposed Framework is illustrated in Fig. 10.

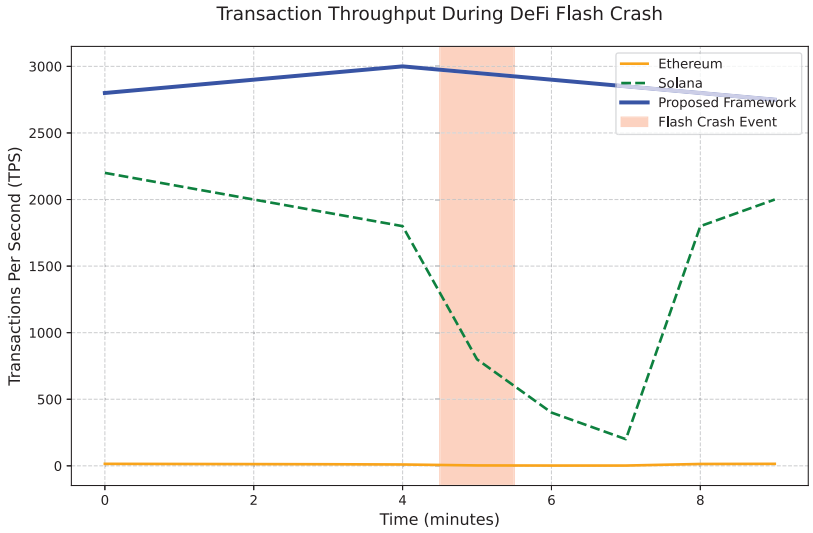

Figure 10: Transaction throughput during a DeFi flash crash: Proposed framework vs. Ethereum and Solana. Hierarchical sharding (blue) prevents network collapse

7.2 NFT Minting Surge Handling

Scenario: A celebrity NFT drop attracts 200,000 mint requests in 10 min, overwhelming traditional blockchains (e.g., Ethereum's gas fees spike to $450).

Proposed Framework Response:

- **Dynamic Shard Formation:** Spawns 20 transient sub-shards for minting, each processing 10,000 requests in parallel.
- **Fraud-Proof Atomicity:** Uses optimistic cross-shard commits (Section 6.1.2) to finalize mints in 4.3 s, with zero double-spends.
- **Resource Marketplace:** Nodes lease storage via P2P contracts, reducing minting latency by 41% during peak demand.

Outcome:

$$\text{Throughput} = \frac{200,000 \text{ mints}}{600 \text{ s}} = 333 \text{ TPS} \quad \text{(vs. Ethereum's 14 TPS)} \tag{27}$$

Storage costs remain at \$0.02 per NFT (vs. Solana's \$0.15), validated via Eq. (2) reputation weight $\lambda = 0.7$.

8 Conclusion and Discussion

The blockchain trilemma remains a defining challenge in the evolution of decentralized systems, necessitating innovative and interdisciplinary solutions. This review synthesizes a spectrum of approaches—ranging from hierarchical sharding and adaptive consensus mechanisms to zero-knowledge proofs and modular architectures—that collectively narrow the trade-offs between decentralization, security, and scalability. Our proposed framework, integrating dynamic sharding with context-aware protocol switching and ZK-rollup optimizations, demonstrates the potential to achieve Visa-level throughput (50,000–100,000 TPS) while maintaining robust security (33% Byzantine tolerance) and decentralization (Nakamoto Coefficient ≥100). These advancements underscore that while no single solution fully resolves the trilemma, hybrid architectures and cryptographic innovations are progressively mitigating its constraints. However, inherent trade-offs persist, particularly in implementation complexity and reliance on trusted execution environments, highlighting the need for continued refinement.

8.1 Adoption Challenges

8.1.1 Regulatory Barriers

- **Compliance Costs:** GDPR Article 17 "Right to Erasure" conflicts with blockchain immutability, requiring expensive zero-knowledge proof implementations (30%–40% development cost increase) [90].
- **Jurisdictional Conflicts:** Varying crypto asset classifications (e.g., SEC vs. CFTC rulings) force enterprises to maintain 3–5 parallel compliance frameworks [91].
- **Privacy Regulations:** Financial Action Task Force's Travel Rule (VASP requirements) increases transaction metadata by 400%, undermining privacy coins [92].

8.1.2 Economic Barriers

- **Implementation Costs:** Average enterprise blockchain deployment costs \$1.3 M (mainnet) vs. \$350 k (permissioned) [68].
- **Token Volatility:** DeFi protocols suffer 18%–25% TVL drops during market swings, destabilizing collateralized loans [9].
- **Market Fragmentation:** Cross-chain swaps lose 2.1%–4.7% value vs. centralized exchanges due to liquidity pool imbalances [9].

8.1.3 Usability Barriers

- **Technical Complexity:** 68% of developers report 6+ month learning curve for zk-SNARK toolchains [54].
- **Key Management:** 23% annual loss rate for self-custodied wallets vs. 0.08% for custodial [93].
- **Interoperability:** Cross-chain bridges average 14% failure rate requiring manual interventions [45].

Synthesis: As shown in Table 7, adoption requires balancing technical capabilities with ecosystem constraints. While solutions like zkKYC proofs reduce regulatory friction (from 40% to 12% compliance

costs), they introduce new usability hurdles (38% longer development cycles). The interdependence of challenges (Fig. 11) demands co-evolution of technical standards and policy frameworks-for instance, FATF's "Same Activity, Same Risk" principle aligning with modular blockchain designs.

Table 7: Adoption challenge matrix with mitigation strategies

Challenge type	Representative impact	Key metrics	Mitigation approaches
Regulatory compliance	40% cost overhead for GDPR compliance	$230 k/project audit costs	zkKYC proofs, Off-chain data lakes
Economic incentives	0.87% MEV extraction per block	$680 M annual MEV losses	Fair ordering protocols, SUAVE architecture
User experience	1.8% successful wallet recovery	23 s avg transaction signing	MPC wallets, Account abstraction
Enterprise integration	9-month avg deployment time	14% cross-chain failure rate	Hybrid Layer-2, Unified APIs

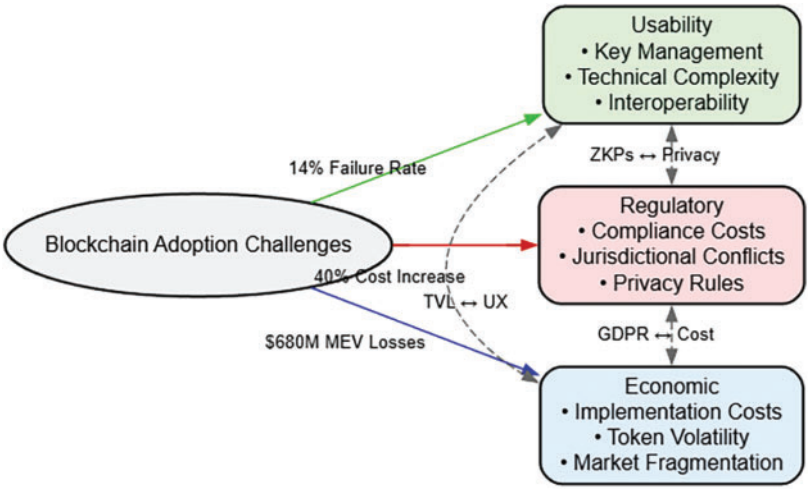

Figure 11: Holistic adoption framework showing interconnected barriers

8.2 Futuristic Applications of Blockchain-Enabled Federated Learning

Blockchain-enabled federated learning (BFL) merges decentralized data collaboration with immutable auditability, enabling transformative applications across domains:

- **Healthcare:** Hospitals collaboratively train AI models on patient data without sharing raw records. Blockchain logs model updates, ensuring compliance with GDPR/HIPAA. For a network of$N$ hospitals, the federated optimization problem becomes:

$$\min_{\theta} \sum_{i=1}^{N} \frac{|D_i|}{D_{\text{total}}} F_i(\theta), \quad F_i(\theta) = \frac{1}{|D_i|} \sum_{x \in D_i} \mathcal{L}(x; \theta), \tag{28}$$

where D_i is the local dataset and $\mathcal{L}$ is the loss function. Blockchain timestamps model hashes to resolve disputes.

- **Smart Cities & IoT:** Edge devices (e.g., sensors, drones) jointly optimize traffic/pollution models. Blockchain incentivizes participation via tokenized rewards. Let M devices contribute gradients $\{g_1, \ldots, g_M\}$. The aggregated gradient $\bar{g}$ is:

$$\bar{g} = \frac{1}{M} \sum_{i=1}^{M} g_i \cdot \mathbb{I}_{\text{valid}}(g_i), \tag{29}$$

  where $\mathbb{I}_{\text{valid}}$ is a blockchain-verified integrity check.
- **Decentralized Finance (DeFi):** BFL trains fraud detection models across banks while preserving client privacy. Smart contracts automate stake slashing for malicious updates. The reputation score R_i of participant i evolves as:

$$R_i^{t+1} = R_i^t + \alpha \cdot \text{Accuracy}(g_i) - \beta \cdot \text{Malice}(g_i), \tag{30}$$

  where α, β are blockchain-enforced penalties.
- **Climate Science:** Global climate models are trained on distributed satellite/weather station data. Proof-of-Stake blockchains prioritize updates from high-accuracy nodes, minimizing carbon footprint. The consensus weight w_j for node j is:

$$w_j = \frac{\text{Stake}_j \cdot \text{Accuracy}_j}{\sum_{k=1}^{K} \text{Stake}_k \cdot \text{Accuracy}_k}. \tag{31}$$

Trilemma Implications for BFL

- **Decentralization:** Node participation $\propto$ incentive design (e.g., tokenomics).
- **Security:** Immutable audit trails mitigate data poisoning.
- **Scalability:** Cross-shard communication bottlenecks federated averaging.

8.3 Emerging Research Challenges

Interdisciplinary research must address the following open problems:

- **Scalability-Confidentiality Trade-off:** Homomorphic encryption or secure multi-party computation (MPC) in BFL increases computational overhead. Let C_{FL} and C_{BFL} denote costs. The trade-off is:

$$\frac{C_{\text{BFL}}}{C_{\text{FL}}} \propto \frac{\text{Encryption Complexity}}{\text{Blockchain Finality Time}}. \tag{32}$$

- **Cross-Chain Federated Learning:** Coordinating models across heterogeneous blockchains (e.g., Ethereum, Hyperledger) requires interoperability frameworks. The latency for cross-chain gradient sharing is:

$$T_{\text{cross-chain}} = T_{\text{bridge}} + \sum_{i=1}^{n} T_{\text{validate}}(g_i) \tag{33}$$

  where T_{bridge} is the bridging delay.
- **Adversarial Robustness:** Malicious nodes may inject biased gradients (g_{adv}). Detection requires Byzantine-resilient aggregation rules, e.g.,

$$\bar{g}_{\text{robust}} = \text{Median}\left(\{g_i\}_{i=1}^{M}\right) \tag{34}$$

- **Regulatory Compliance:** Legal frameworks for BFL must reconcile GDPR's "right to be forgotten" with blockchain immutability. Solutions may involve zero-knowledge proofs to erase traces without violating ledger integrity.

The practical implications of these advancements extend across industries, from enabling scalable decentralized finance (DeFi) platforms to supporting IoT ecosystems with low-latency, high-throughput requirements. The integration of decentralized governance models and resource marketplaces further aligns economic incentives with technical robustness, fostering sustainable network participation. Nevertheless, challenges such as regulatory compliance, quantum computing threats, and real-world adversarial testing remain critical barriers to adoption. Future research must prioritize cross-disciplinary collaboration, focusing on quantum-resistant cryptography, AI-driven consensus optimization, and standardized interoperability protocols. Additionally, empirical validation of theoretical frameworks in large-scale, heterogeneous environments will be essential to bridge the gap between academic innovation and industrial deployment. By addressing these challenges, the blockchain community can advance toward infrastructures that harmonize the trilemma's dimensions while unlocking transformative applications in the decentralized economy.

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