State of the Art Review Paper: Scalability in Blockchain using Node Sharding and Directed Acyclic Graphs.

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***Abstract*—This research investigates ten pivotal papers that explore Directed Acyclic Graphs (DAGs) and node sharding techniques to enhance blockchain scalability for the Industrial Internet of Things (IIoT) and 6G networks. The objective is to overcome the limitations of traditional blockchain architectures, such as low throughput and high latency, which do not meet the requirements of high-volume, real-time data processing in IIoT and 6G applications. The study examines the adaptations and optimizations of DAGs and sharding for resource-constrained devices and extensive network scales in future telecommunications and industrial systems. By integrating these technologies, the research reduces transaction confirmation times and enhances decentralization, thereby securing IIoT and 6G ecosystems against various security threats. The results will present current capabilities, pinpoint technology gaps, and suggest future research directions for developing robust, efficient, and scalable blockchain frameworks. This advancement will promote innovation in industrial automation and smart infrastructure.**

***Index Terms*—Directed Acyclic Graphs, Node Sharding, Blockchain Scalability, Industrial Internet of Things, 6G Networks**

I. Introduction

In the rapidly evolving world of digital infrastructure, blockchain technology has emerged as a cornerstone for developing secure and decentralized systems. However, as the adoption of blockchain extends across various sectors, particularly in areas requiring high transaction throughput like financial services, healthcare, and especially the Industrial Internet of Things (IIoT) and 6G telecommunications, its inherent scalability limitations have become increasingly apparent. Traditional blockchain architectures often struggle with low throughput and high latency, rendering them ineffective for high-volume, real-time data processing required in modern IIoT and 6G applications.

To address these challenges, recent advancements in blockchain scalability have focused on two promising technologies: Directed Acyclic Graphs (DAGs) and node sharding. DAGs offer an innovative approach to data structuring and validation, allowing multiple transactions to coexist without awaiting sequential block formation, thus enhancing throughput and reducing latency. On the other hand, sharding partitions the blockchain into smaller, manageable pieces or "shards," each capable of processing transactions independently, thereby multiplying the network's overall capacity.

These technologies are not just theoretical enhancements but are pivotal in the practical deployment of blockchain in environments constrained by high data demands and the need for rapid processing. For instance, in IIoT settings, where myriad devices continuously transmit data, the ability to quickly process and secure data without bottlenecks is crucial. Similarly, the upcoming 6G networks, which promise even higher data rates and lower latency, necessitate a blockchain solution that can match their throughput requirements without compromising security or decentralization.

The hybrid structure combining DAGs and sharding presents a comprehensive solution by leveraging the strengths of both technologies to meet the stringent demands of modern applications. This hybrid approach not only promises to enhance transaction processing capabilities but also ensures that blockchain can scale effectively and securely, maintaining its foundational principles of decentralization and trustlessness in more complex and demanding environments like those anticipated with the proliferation of IIoT and the roll-out of 6G networks.

II. Background

Blockchain scalability is crucial for managing growing transaction volumes in areas like cryptocurrencies and smart contracts. As the technology advances alongside developments like 6G, which provides higher data rates and lower latency, blockchain must adapt to avoid becoming a bottleneck in these enhanced communication networks.

Directed Acyclic Graphs (DAGs) are critical in graph theory. They feature directed edges and a non-cyclical structure that prevents returning to the start vertex. This feature enables DAGs to optimize processes such as task scheduling and blockchain optimization by ensuring a logical, non-repetitive order of data processing critical for systems needing precise dependency resolution.

Node sharding, a method for enhancing blockchain scalability, partitions the network into smaller, independent ”shards” for parallel transaction processing. This increases capacity and addresses the scalability trilemma of balancing decentralization, security, and scalability. However, it also brings challenges like maintaining data consistency and managing communications between shards.

III. Related Work

A. Enhancing Blockchain Scalability through Sharding

The paper aims to address the scalability challenges of blockchain systems by proposing a sharding-based framework [1]. The researchers focus on enhancing transaction throughput by introducing improvements in Byzantine consensus protocols and shard formation techniques. They aim to overcome the limitations of existing systems by leveraging trusted hardware, such as Intel SGX, for high-performance consensus and secure shard formation.

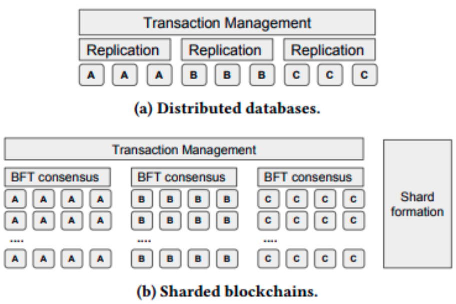

Fig. 1. Sharding protocols in traditional databases vs. blockchains. [1]

Results from the study demonstrate significant advancements in transaction throughput, with over 3,000 transactions per second achieved in realistic settings on the Google Cloud Platform. Additionally, the framework maintains high transaction throughput in multi-region setups with hundreds to thousands of nodes. However, the paper acknowledges limitations, including dependence on trusted hardware and complexity in protocol coordination. These limitations raise concerns about the general applicability of the framework in environments lacking reliable hardware and the potential inefficiencies in managing distributed transactions across shards.

B. Node Sharding for Improved Transaction Processing

Introducing a scalable blockchain architecture aimed at improving transaction processing efficiency and security, the paper proposes the Ostraka architecture, which implements node sharding to distribute transaction processing across node shards [2]. Through a distributed block validation mechanism and transaction distribution using hashing with unique node-specific ”salt,” the Ostraka architecture achieves linear scalability and ensures comparable security to traditional systems. Results from the study demonstrate impressive scaling performance, achieving up to 400k transactions per second, while maintaining security levels equivalent to traditional systems.

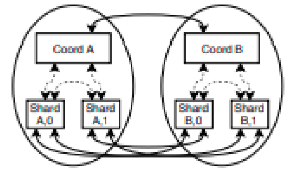

Fig. 2. Two connected Ostraka nodes, with intra-node connections. [2]

However, the paper identifies limitations related to resource intensity and complexity in implementation due to the distributed nature of the architecture. These limitations highlight challenges in managing computational resources per node and the complexity involved in maintaining and debugging the system.

C. Layered Sharding for Enhanced Blockchain Scalability

The paper presents a novel approach to enhance blockchain scalability through layered sharding [3]. The researchers aim to efficiently handle cross-shard transactions and leverage advanced nodes’ capabilities to improve overall network performance. The methodology involves implementing a layered sharding approach, where nodes operate in multiple shards, and developing a cooperative cross-shard consensus mechanism to validate and execute transactions securely.

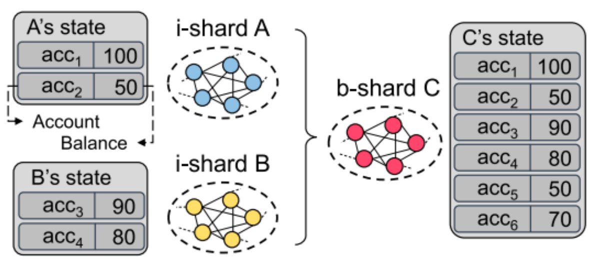

Fig. 3. Illustration for a layered sharding for i-shard A, B and b-shard C. [3]

Results from the study indicate a significant improvement in transaction throughput, with up to 3.2 times enhancement compared to existing sharding techniques. Achieving around 3821 transactions per second for 20 shards demonstrates the effectiveness of the proposed layered sharding approach. However, the paper acknowledges limitations, such as assumptions about node distribution and capacity, reliance on bridging shards’ capability, and the complexity of ensuring consistent security across all shards. These limitations emphasize the need for further research to address challenges in practical implementation and security safeguards against potential breaches or failures.

D. Enhancing Sharding Capabilities with Transactional Dependencies

The paper titled ”TxChain: Scaling Sharded Decentralized Ledger via Chained Transaction Sequences” introduces Tx-

Chain [4], a novel distributed ledger technology that employs sharding to address scalability issues in blockchain systems. The core innovation of TxChain lies in its use of transaction sequences for each account, organized in a Merkle Patricia Tree structure, to facilitate efficient transaction processing within shards and ensure accurate synchronization across them. This design allows for parallel transaction processing, which significantly boosts throughput. According to the findings, doubling the number of shards results in a throughput increase of approximately 1.59 to 1.89 times as can be seen from Fig 4, demonstrating the system's scalability. However, the scalability benefits diminish with additional shards due to the complexities and overhead associated with maintaining complete ledger copies across all shards.

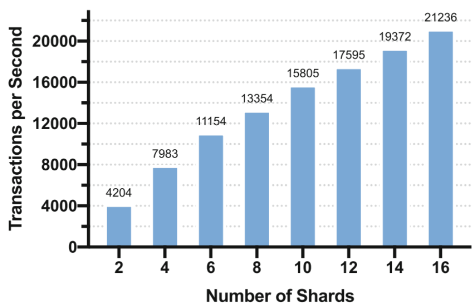

Fig. 4. Throughput Scalability (Throughput vs Number of shards) [4]

Moreover, the paper discusses the challenges associated with TxChain, including the scalability of storage due to the replication of the entire ledger in each shard and the complexities involved in managing transactions across different shards. These aspects introduce significant overheads that could hinder performance as the network expands. Using a Transaction Sequence Conversion (TSC) consensus mechanism is a pivotal element in maintaining transaction order and consistency across the network, showcasing a sophisticated approach to managing shard consistency without excessive communication overhead [4].

E. Cooperation-Based Sharding Architecture

The paper "Benzene: Scaling Blockchain with Cooperation-Based Sharding" introduces a novel sharding approach in blockchain technology that enhances system performance through a cooperative consensus mechanism among shards, deviating from traditional non-cooperative frameworks [5]. In this model, a dual-chain architecture separates transaction recording and consensus execution into proposer and vote chains, respectively, facilitating parallel processing while ensuring security and fault tolerance [5]. Cross-shard verification is performed by nodes equipped with Trusted Execution Environments (TEEs), which validate blocks from other shards and provide validation proofs, depicted by dotted blue arrows in Fig. 5. Additionally, miners across all shards engage in a cross-shard voting consensus, using TEE proofs to vote and confirm the most supported block, as illustrated by solid red arrows. The integration of TEEs within each shard optimizes the validation process by providing transaction validation proofs from other shards, reducing the load on individual nodes and enhancing throughput efficiency. According to the study, Benzene achieves a significant throughput of 32,370 transactions per second with 50 shards, markedly surpassing traditional systems like Bitcoin [5].

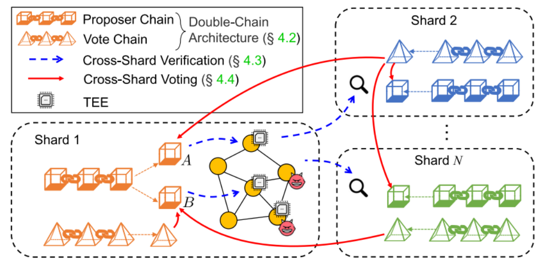

Fig. 5. Architecture of Benzene [5]

The paper compares the confirmation latency of Benzene to a Bitcoin-like system across various shard counts, noting Benzene's efficient scalability with latency stabilizing at low levels up to 200 shards, while the Bitcoin-like system achieves similar stability only beyond 50 shards [5]. It also highlights potential security vulnerabilities in Benzene due to reliance on TEEs, which are susceptible to attacks like rollbacks, and notes a scalability plateau in throughput at around 400 shards due to the limited number of available TEEs, indicating a critical system limitation under larger network conditions [5].

F. Compacted DAG Technique to Scale Blockchain

The paper "An Efficient and Compacted DAG-Based Blockchain Protocol for Industrial Internet of Things" introduces CoDAG, a blockchain protocol optimized for IIoT using a compacted DAG architecture to enhance scalability and transaction speed [6]. CoDAG enables multiple concurrent block appendings, achieving a throughput of 1151 transactions per second, significantly outperforming traditional blockchains like Bitcoin and Ethereum. It organizes IIoT devices into miners and gateways to optimize data flows and includes multiple operational layers like the DApp and Chain Layers to support decentralized applications and ensure data integrity [6].CoDAG's architecture proposed by the authors as shown in Fig. 6 systematically leverages the heterogeneous capabilities of various IIoT devices by categorizing them into miners, gateways, and nodes, each performing roles aligned with their computational and communication capacities. Miners maintain the ledger, while gateways facilitate transaction and data flows, thus optimizing the network's resource use and operational efficiency [6]. In experimental conditions, CoDAG reached 1151 transactions per second (tps) with a block size of 2 MB and a width of 15, a performance which is 164 times the throughput of Bitcoin and 77 times that of Ethereum.

However, the protocol is noted to suffer from instability under high transaction rates potentially, and struggles with

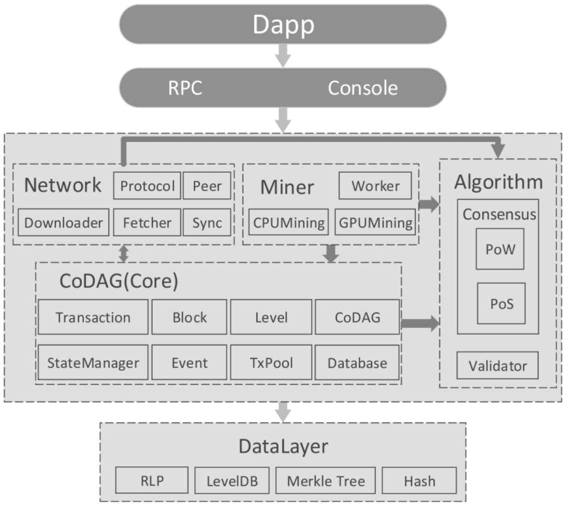

Fig. 6. Implementation Framework with CoDag [6]

large data volumes remain a concern. The authors suggest future work will focus on these limitations, aiming to enhance the security and throughput of CoDAG further. This research contributes a pivotal advancement in blockchain technology, offering a scalable and efficient solution potentially transformative for IIoT frameworks.

G. Signaling Protocol to Scale DAG-based Blockchains

The paper introduces a novel approach to tackle the core issues of revenue and throughput dilemmas in DAG-based blockchain systems [7]. TIPS swiftly disseminates transaction data across the network by incorporating a Bloom filter into the block header. This strategy reduces transaction inclusion collisions, which typically hamper system performance by dividing rewards among miners and impeding throughput due to increased propagation delays.

TIPS's core innovation lies in separating the block header's transmission, which contains the Bloom filter signal, from the block body. This separation enables rapid spread of crucial transaction inclusion data, allowing miners to adjust their transaction inclusion strategies in advance to prevent collisions. This method not only enhances miner revenues by facilitating the inclusion of high-fee transactions without the risk of collision but also boosts system throughput by supporting larger block sizes without corresponding increases in propagation delay. The researchers thoroughly analyze the architecture and potential impacts of TIPS through game-theoretic methods and simulations, illustrating that TIPS can resolve the prevalent revenue and throughput issues in current DAG-based blockchain systems. They provide experimental proof that TIPS achieves near-optimal block capacity utilization and significantly improves system throughput compared to conventional protocols. TIPS can achieve a block capacity utilization of around 90% and can provide a system throughput (TPS) that is up to 5 times higher than the standard protocol. However, the study recognizes certain limitations, such as the computational and communication overhead introduced by the Bloom filter-based signaling. Additionally, although the Bloom filter effectively minimizes false positives, it does not completely eradicate them, potentially leading to slight inaccuracies in transaction signaling. Due to these overheads it is also not well suited for IOT environments.

H. Evaluating IOTA: a DAG-based Blockchain for IOT Environments

The study in [8] explores the suitability of IOTA, a DAG-based blockchain, for Internet of Things (IoT) environments, identifying several limitations of traditional blockchain systems like Bitcoin and Ethereum, including low transactions per second (TPS), substantial computation demands, and high costs. These constraints render such systems impractical for IoT applications, which require high throughput and low latency. The paper presents a methodological approach by setting up a private IOTA network involving 35 Intel NUCs to simulate an IoT ecosystem. This setup included various functionalities like an automatic transaction initiator, a real-time status monitor, and a double-spending attacker, enhancing the realism of the network testing. The architecture of IOTA, as

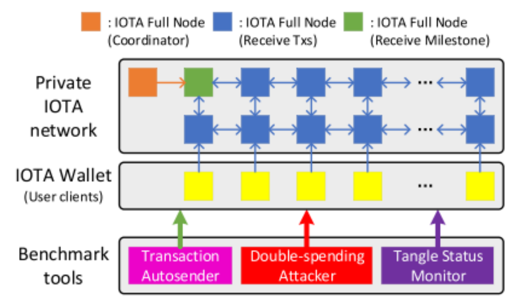

Fig. 7. Private IOTA System Architecture [8]

shown in Fig.7, leverages a DAG structure called the Tangle, where each transaction forms a node. This structure allows for higher scalability and throughput by enabling transactions to process other transactions, thus potentially offering a superior solution for IoT scenarios, which demand handling large volumes of micro-transactions swiftly. The experimental results from the paper illustrate that IOTA can manage a system throughput of about 25 TPS with optimal conditions but noted a slight decrease in performance when the network is scaled up. It also demonstrated robustness in handling network attacks like double-spending and off-syncing, showcasing recovery capabilities with a decent recovery speed.

However, the study highlighted several limitations. One significant issue is the increased network synchronization overhead when adding more full nodes, which affects the system's scalability and acts as a bottleneck. Another critical point is the reliance on a Coordinator node, which introduces a point of centralization and a potential single point of failure, thus deviating from the decentralized nature sought in blockchain technologies. These findings suggest areas for potential improvement in ensuring IOTA's architecture can be reliably decentralized while maintaining its performance and robustness in larger scaled IoT environments.

I. Modifying Block Structure for Scalability

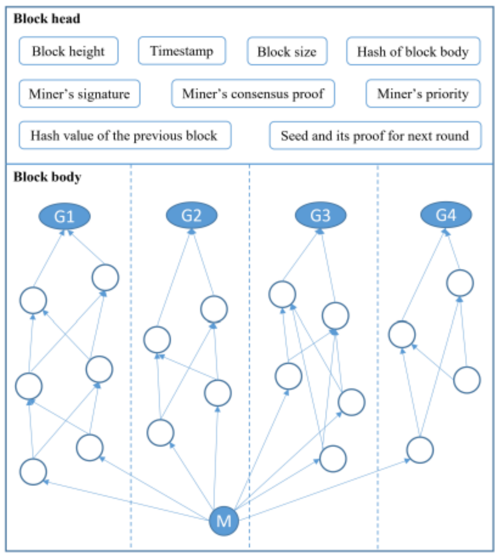

Fig. 8. DAG Block Structure [9]

The paper [9] proposes an innovative solution to the limitations faced by traditional blockchain systems such as Bitcoin, which struggle with low transactions per second (TPS) and high latency. This research is particularly timely, as these shortcomings present significant hurdles in cryptocurrency markets. The DAG-BLOCK architecture, shown in Fig. 8 leverages a DAG within each block to facilitate simultaneous transaction processing, aiming to preserve the linear chain structure while controlling DAG size. This approach introduces "open blocks," allowing user nodes to partake in transaction verification, thereby reducing miners' load and decentralizing the process further. The architecture outlined in the paper is dual-layered, as shown in Fig. 9 mixing decentralized peer-to-peer networks with centralized components, where each miner caters to a specific user segment, diminishing the breadth of transactions they manage. This segmentation is designed to cut down on the communication overhead and security vulnerabilities that could arise from increased user participation in the verification process.

Empirical results are encouraging, with the DAG-BLOCK system reducing transaction confirmation times to mere seconds and achieving throughputs between 50-100 TPS, far exceeding the capabilities of Bitcoin and Ethereum. Where IOTA's performance declined with additional nodes, DAG-BLOCK's architecture provides a systematic solution to manage network growth and maintain high throughput, offering an intriguing alternative for scaling blockchain systems in cryptocurrency markets. Despite these advancements, there are noted limitations. The segmentation of markets introduces

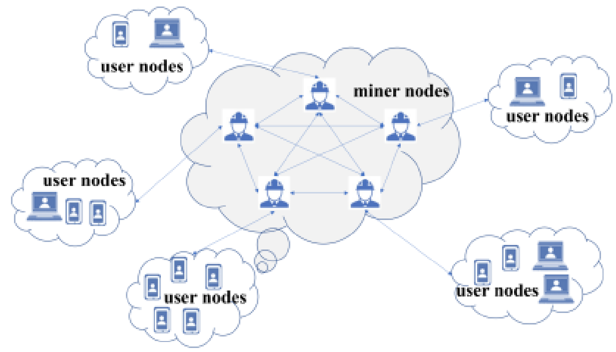

Fig. 9. Network Market Architecture [9]

complexities in managing synchrony, and increased user participation may lead to added communication overhead and potential security risks.

J. Blockchain for 6G network

The study by [10] introduces a novel DAG-based Blockchain SHarding (DASH) scheme to tackle scalability and security issues in 6G networks. This approach utilizes sharding for efficient data recording and a Directed Acyclic Graph (DAG) for secure blockchain updates, aiming to boost transaction throughput and resource efficiency. A significant feature is the use of a global DAG by each sharding committee, which records all block existences for mutual verification and broadcasts only block headers to minimize communication overhead. The architecture ensures the integrity of transactions and employs a computationally efficient consensus algorithm to optimize miner efforts and resource use [10].

Additionally, the paper describes implementing the DASH system in a spectrum-sharing context, starting with a genesis block that announces public keys and licensed bands of incumbents. Through smart contracts, the network is divided into committees, setting up spectrum-sharing policies and protecting incumbents. This paper details the spectrum-sharing process, from base station requests to frequency band access authorization. The resource-efficient consensus algorithm encourages miners to devise spectrum allocation strategies focusing on fairness and efficiency rather than solving hash puzzles. This approach not only improves fairness and efficiency in spectrum-sharing but also, as demonstrated in the illustrative results (fig 10), allows for more effective spectrum allocation and higher network utility compared to traditional Proof of Work (PoW) blockchain methods [10].

Table I provided offers a comparative study of all the papers based on the literature review. It compares each study, with their methodologies, technology used, novelty highlighting differences and similarities in approaches to blockchain technology, scalability, and integration with real life applications like IIoT and 6G. This comparison allows for a clearer understanding of the current research landscape and identifies potential areas for future investigation.

TABLE I
COMPARISON OF RESEARCH PAPERS ON SCALABILITY IN BLOCKCHAIN

Serial No.	**Conference and Year**	**Technique Used**	**Technology Used**	**Software and Hardware Used**	**Real World Application**	**Novelty**	**Limitations and Future Scope**
1	IEEE ICC 2021	Directed Acyclic Graph (DAG) with sharding [10]	DAG blockchain and sharding enhance 6G network capabilities; includes decentralized storage access.	Software for 6G networks; hardware unspecified.	Improves energy and data sharing in 6G; enhances spectrum management efficiency.	Combines DAG with sharding for scalability; introduces efficient consensus and federated learning in blockchain.	Challenges in blockchain consistency and security-performance trade-offs need further study.
2	IEEE TCSS 2024	Weighted tip selection and cryptography lottery protocol [9]	Uses cryptography for miner selection and transaction verification to prevent double-spending.	Focuses on scalability and consensus in cryptocurrency markets.	Ensures secure transactions and consistent state synchronization in cryptocurrencies.	Introduces random leader selection and dust transaction prevention.	Needs improvements in scalability and ongoing security against double-spending.
3	IEEE IoT-J 2022	DAG-based approaches for IoT [8]	Uses IOTA and traditional blockchain systems; evaluates IoT security.	GPU, FPGA, ASIC, ReRAM; IOTA system setups.	Analyzes IoT security and robustness; aids system architects.	Examines IOTA's performance and suggests optimization for IoT.	Aims to enhance database performance and speed up validations.
4	IEEE JSAC 2022	Transaction Inclusion Protocol with Signaling (TIPS) [7]	Employs Bloom filters to manage false positives in transaction signaling.	Uses Bloom filters; validated through theoretical and experimental means.	Enhances transaction efficiency and security in blockchain systems.	Reduces collision and defends against service attacks; analyzes miners' revenue strategies.	Future work on signal simplification and dynamic miner strategies needed.
5	IEEE TII 2020	Compact DAG (CoDAG) protocol [6]	Combines PoW and Byzantine agreement in a hybrid consensus for IIoT.	Implemented for IIoT efficiency; CoDAG-based architecture.	Improves IIoT system efficiency and service reliability.	Achieves high throughput; enhances IIoT architecture efficiency.	Future work to explore hybrid consensus more deeply.
6	IEEE TPDS 2023	Cooperation-based PoW sharding [5]	Employs ECDSA and SHA-256 in Benzene prototype; uses Intel SGX.	Python and MPI for parallel node operation.	Benzene improves performance and scalability in blockchain.	Introduces double-chain architecture and fault-tolerant cross-shard verification.	Needs better cross-shard cooperation; faces security challenges.
7	DASFAA 2022	Transaction Sequence Conversion (TSC) [4]	Uses sharding and a TSC-based consensus; Golang for implementation.	Golang on Intel Xeon CPUs; distributed across multiple machines.	Suitable for scalable decentralized ledgers.	Introduces a novel DL with high scalability and low latency.	Points out inconsistencies in DAG-based DLs; calls for data structure improvement.
8	IEEE JSAC 2022	Layered sharding via CoSplit [3]	Utilizes collective signatures and trusted execution for sharding.	Amazon EC2 machines; secure parameters set for testing.	Aids blockchain scalability and throughput on Ethereum.	Enhances performance with a relay mechanism for cross-shard transactions.	Lacks discussion on limitations; future work not specified.
9	IEEE S&P 2021	Ostraka node sharding and block validation [2]	UTXO model; deterministic transaction mapping.	Utilizes the UTXO model; tested with various node setups.	Enhances blockchain scalability and security without losing consensus quality.	Maintains performance and security with scalable node architecture.	Focuses on optimizing node-sharding techniques for future performance gains.
10	SIGMOD 2019	Attested HyperLedger (AHL) protocol [1]	Implements SGX for secure sharding in Hyperledger Fabric.	Uses Intel SGX on Xeon CPUs; local cluster setup.	Improves transaction throughput in permissioned blockchain systems.	Enhances throughput and security in sharding; extensive protocol evaluation.	Aims to overcome BFT scalability issues and improve shard security.

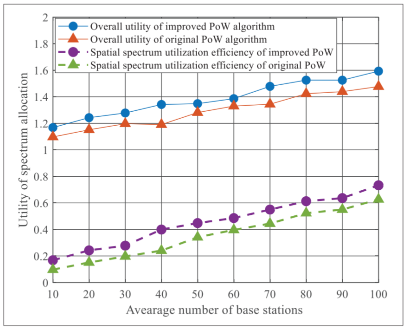

Fig. 10. Comparsion of the utility of proposed approach and PoW. [10]

IV. Research Gaps

In reviewing the discussed research papers on scaling blockchain using various techniques, we identify key areas for future research and methodological advancements:

- **Security and Robustness of Consensus Mechanisms:** Existing research highlights security concerns with sharded and DAG-based blockchains. A hybrid consensus mechanism is proposed, combining Byzantine Fault Tolerance (BFT) within shards for quick processing and Proof-of-Stake (PoS) across shards to enhance security and synchronization.
- **Cross-Shard Transaction Integrity and Efficiency:** Issues with efficient cross-shard transactions and maintaining ledger accuracy are prevalent. Strengthening cross-shard security through PoS mechanisms and improving intra-shard efficiency with BFT-like algorithms could facilitate rapid consensus among nodes and enhance the network's performance.

These research areas aim to enhance blockchain scalability, throughput, and security, crucial for deployment in large-scale, demanding settings.

V. Conclusion

This review discusses the enhancement of blockchain scalability through the integration of Directed Acyclic Graphs (DAGs) and node-sharding techniques. These methods address the high throughput and low latency demands of the Industrial Internet of Things (IIoT) and 6G networks, with DAGs reducing transaction confirmation times to boost throughput, and node sharding distributing the processing load to enhance system efficiency and security. The review also highlights persistent scalability challenges in consensus algorithms and the difficulty of maintaining blockchain integrity across various applications.

Future research should develop advanced hybrid consensus models that merge Proof of Stake (PoS) with Byzantine Fault Tolerance (BFT) to improve scalability and robustness. Innovating transaction protocols will be key for enhancing network performance and facilitating seamless cross-shard transactions. These optimizations are crucial for blockchain evolution to support broad 6G networks and advanced IIoT frameworks, aiming to minimize communication overhead and boost transactional integrity across shards, thereby maximizing blockchain's potential in next-generation networks and applications.

VI. Proposed Methodology

Taking all the insights from the papers, after analysis the research gaps, technical requirements, future research could include the following hot topics.This research proposal details a multi-pronged strategy to enhance blockchain scalability and throughput through the following technical innovations:

- **Hybrid Consensus Mechanism:** Combines Byzantine Fault Tolerance (BFT) within shards for faster transaction processing and Proof-of-Stake (PoS) across shards to enhance security and synchronization. BFT accelerates consensus by allowing some nodes to verify transactions, boosting intra-shard efficiency, while PoS manages inter-shard interactions, ensuring ledger accuracy and increasing overall throughput.
- **Optimized transaction propagation:** Improve the efficiency of transaction propagation and synchronization across the DAG network. Techniques like compact transaction representations, intelligent gossiping protocols, and topology-aware routing can help reduce the communication overhead and latency while ensuring reliable and consistent transaction dissemination

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