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Building Scalable Blockchains: Strategies, Trade-Offs, And Future Directions

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Abstract: The potential of blockchain technology to revolutionise several sectors has attracted a lot of interest in recent years. Scalability has, however, become an important issue that prevents the mainstream adoption of blockchain networks as their size and usage continue to increase. This study provides a thorough analysis of the scalability problems in blockchain networks and considers various remedies. We examine the basic limits of the blockchain designs that are currently in use, including those related to consensus techniques, network capacity, and storage needs. We also look into a number of scaling ideas that have been put up in the literature, including layer-2 protocols, sidechains, off-chain transactions, and sharding. Additionally, we go over the compromises made by various solutions and assess how well they work to increase blockchain scalability. This study attempts to give important insights into the scalability issues blockchain networks confront and proposes a path for further study in this field.

Index terms - Blockchain, Scalability, Consensus Algorithms, Sharding, Off-chain Transactions, Sidechains, Layer-2 Protocols.

I. Introduction:

Blockchain technology has drawn a lot of interest from a variety of businesses since it was first used to underpin cryptocurrencies. Blockchain networks' scalability problems have, however, become a significant barrier to their mainstream acceptance as they continue to expand in size and use. In order to identify potential solutions that have been presented and to give an overview of the research that has been done on tackling scalability issues in blockchain networks, a literature study was undertaken.

II. Literature Review

The difficulties blockchain networks have in scaling up have been noted by a number of research. Eyal and Sirer (2018) highlight the trade-offs involved in the "trilemma" of attaining scalability, security, and decentralisation in blockchain systems. As significant scalability barriers, they highlight the low transaction throughput and lengthy confirmation times.

Consensus algorithms are essential to the scalability of blockchain technology. The core Bitcoin algorithm, Nakamoto consensus, has a limited transaction throughput. To increase scalability, some scholars have suggested substitute consensus techniques. For instance, Ethereum's planned switch from Proof-of-Work (PoW) to Proof-of-Stake (PoS) consensus seeks to improve scalability by cutting down on energy use and speeding up transaction processing (Wood, 2018). [1].

Sharding has become a potential method for boosting blockchain networks' scalability. By dividing the blockchain into manageable chunks, or "shards," sharding makes it possible to execute transactions in parallel. In order to maximise resource utilisation and scalability, Zamyatin et al. (2020) offer a sharding method called ElasticSharding that dynamically modifies the number of shards based on network circumstances. [2].

By lightening the load on the primary blockchain and enhancing scalability, off-chain transactions and layer-2 protocols are used. Payment channels, like the Lightning Network (Poon & Dryja, 2016), enable parties to transact without registering every transaction on the blockchain, enabling quicker and less expensive off-chain transactions. The aggregation and compression of numerous transactions into a single record on the primary blockchain is made possible by layer-2 protocols like Plasma (Poon & Buterin, 2017) and Rollups, greatly enhancing scalability. [3].

By shifting specific kinds of transactions or smart contracts to different chains, sidechains offer a further method for boosting scalability. Back et al. (2014) provide a two-way pegging system that permits the movement of assets between the main blockchain and sidechains, encouraging interoperability while easing scalability restrictions. [4].

Other strategies have been investigated by researchers to increase blockchain network scalability. These include pruning methods to reduce the amount of storage needed for blockchain data (Lu et al., 2019), block propagation protocol optimisation to increase network bandwidth utilisation (Dinh et al., 2018), and the use of cryptographic primitives like zero-knowledge proofs to simultaneously improve privacy and scalability (Ben-Sasson et al., 2014). [5].

Blockchain has been used in many different industries, including cryptocurrencies, food traceability, identity management, and even market forecasting, as a newly developed and revolutionary technology. Both business and academics have given it significant attention and undertaken a considerable deal of study to uncover its immense potential. In this study, we unroll and organise the blockchain-related discoveries and scientific findings in many different ways based on the literature and industry whitepapers. In particular, we divide blockchain technology into four categories and conduct an extensive analysis of the consensus mechanisms, the blockchain network, and the applications. Various blockchain applications are classified according to their sectors, particularly in the Internet of Things (IoT) [12].

The Lightning Network (LN), a second-layer protocol built on top of the Bitcoin blockchain, is a cutting-edge digital payment system that provides both consumers and companies with enhanced convenience, speed, and cost-effectiveness. The complexity and breadth of the different business LN-related applications, as well as pertinent adoption/implementation issues, are all covered in a very little amount of literature. This research seeks to further knowledge of the LN's traits, its potential to improve business operations, and its application across many industries while taking into consideration adoption and implementation issues. [13].

This paper provides an introduction to blockchain technology and its legal implications. The paper consists of two parts. The first part looks at the technology behind the hype. It explains how blockchain technology works and can be deployed in various ways to create applications with different features, including open, distributed and closed, and centralised platforms. The second part analyses the technology's implications for several areas of law that will be relevant to companies and other organisations that seek to use blockchain technology, namely: contract law, data protection law, securities law, property law, intellectual property, and company law [14].

The adoption of blockchain and Distributed Ledger Technology is continuously increasing and offering solutions to various application areas. In the last few decades, much more developments in various features are seen to improve the performance, but still scalability is becoming the bottleneck for the performance enhancement. The scalability problem further leads to severe delays and high costs in a bitcoin network. Nowadays, the real-time transactions in cryptocurrencies need to be scaled up from seven transactions per second to thousands of transactions per second to handle real-life problems in the field of visa, healthcare, flights, etc. In this paper, a detailed study on the scalability issues, Proof of Work, and Practical Byzantine Fault Tolerant in blockchain was given. It also explored and analysed the recent promising research areas in blockchain scalability such as net neutrality, sharding, side-chain, and off-chain scaling through blockchain distributed networks along with their effects [15].

As a promising solution to blockchain scalability, sharding divides blockchain nodes into small groups called shards, splitting the workload. Existing works for sharding, however, are limited by cross-shard transactions, since they need to split each cross-shard transaction into multiple sub-transactions, each of which costs a consensus round to commit. In this paper, we introduce PYRAMID, a novel sharding system based on the idea of layered sharding.

In PYRAMID, the nodes with better hardware are allowed to participate in multiple shards and store the blockchains of these shards thus they can validate and execute the cross-shard transactions without splitting. Next, to commit the cross-shard transactions with consistency among the related shards, we design a cooperative cross-shard consensus based on collective signature-based inter-shard collaboration.

Furthermore, we present an optimization framework to compute an optimal layered sharding strategy maximizing the transaction throughput with the constraint of system security and node resource. Finally, we implement a prototype for PYRAMID based on Ethereum and the experimental results reveal the efficiency of PYRAMID in terms of performance and scalability, especially in workloads with a high percentage of cross-shard transactions. PYRAMID improves the throughput by up to 3.2 times compared with the state-of-the-art works and achieves about 3821 transaction per seconds for 20 shards [16].

III. Scalability Approaches and Techniques

Due to the inherent constraints of conventional blockchain topologies, blockchain scalability has been a focus of study and development. The scalability issues blockchain networks confront have been addressed using a variety of strategies and methods. Here are a few noteworthy ones:

Sharding: The process of sharding entails breaking the blockchain network up into smaller segments known as shards. To enable parallel processing and boost total transaction performance, each shard is in charge of handling a portion of the transactions. One well-known example of a project that intends to use sharding to improve scalability is Ethereum 2.0.

Off-Chain Transactions: By executing certain transactions off-chain, off-chain transactions seek to lighten the load on the main network. Participants can execute several transactions off-chain using payment channels like the Lightning Network, with the final result being settled on the blockchain. The speed and scalability of transactions are considerably increased by this method.

Layer-2 Protocols: In order to enable more effective and scalable transactions, layer-2 protocols install further layers on top of the primary blockchain. The computational and storage cost is decreased by these protocols, which combine numerous transactions into a single entry on the main chain. Examples include Plasma, State Channels, and Rollups (including ZK-Rollups and Optimistic Rollups).

Sidechains: Interoperable with the main blockchain are sidechains, which are independent blockchains. They relieve the main chain's scalability restrictions by offloading particular types of transactions or smart contracts to other chains. With the help of sidechains, it is possible to scale particular functionality while keeping the main chain connected.

Consensus Algorithm Optimization: The scalability of a blockchain network is directly impacted by the consensus method utilised. Although safe, Proof-of-Work (PoW) consensus has a finite ability to scale owing to its processing demands. By lowering energy consumption and transaction validation cost, Proof-of-Stake (PoS) and other consensus algorithms, such Delegated Proof-of-Stake (DPoS) and Practical Byzantine Fault Tolerance (PBFT), enable improved scalability.

Pruning and Compression Techniques: Pruning refers to the removal of extraneous data from the blockchain, such as transaction history that is no longer required for validation. This enhances scalability and lowers the need for storage. In order to make the blockchain smaller and more efficient, compression algorithms work to compress and consolidate many transactions into more manageable forms.

IV. Case studies and Implementation

Case studies and actual blockchain scaling implementations offer examples of how scalability issues are handled in the real world. The following are a few noteworthy case studies and applications.:

Ethereum 2.0: One of the most popular blockchain platforms, Ethereum, is undergoing a significant update known as Ethereum 2.0 or Eth2. With this version, several scalability alternatives will be included, including the use of the Beacon Chain sharding method. Ethereum 2.0 seeks to greatly boost transaction throughput and enhance scalability while retaining decentralisation by splitting the network into several shards.

Lightning Network: On top of the Bitcoin blockchain, there is a layer-2 scaling solution called the Lightning Network. It creates payment channels between participants, enabling off-chain transactions. Compared to on-chain Bitcoin transactions, the Lightning Network allows for quicker and less expensive transactions. It has also showed excellent scalability advantages.

Zilliqa: Sharding is a key scalability method used by the blockchain network Zilliqa. It uses a special form of sharding known as "sharding by design," in which the network is split up into several shards that may handle transactions simultaneously. Zilliqa is one of the most scalable blockchain networks now in use because to its high throughput and capacity to execute thousands of transactions per second.

Polygon (formerly Matic Network): For Ethereum, Polygon is a layer-2 scaling solution that offers a foundation for creating scalable and functional blockchain networks. By utilising sidechains, which are connected to the Ethereum mainnet, it is scalable. By allowing quick and inexpensive transactions, Polygon helps the Ethereum network scale more easily and lessens network congestion.

Binance Smart Chain (BSC): A blockchain platform called Binance Smart Chain was created by the Binance cryptocurrency exchange. To improve scalability, it combines consensus techniques and optimisations. In contrast to the Ethereum network, BSC uses a dual-chain design and the Proof-of-Staked Authority (PoSA) consensus process to achieve quicker block confirmation times and increased transaction throughput.

Optimism and Arbitrum: Based on Optimistic Rollups, Optimism and Arbitrum are layer-2 scaling solutions that attempt to scale Ethereum smart contracts. With the help of these methods, many transactions may be combined into a single batch, lowering the computational load on the Ethereum mainnet. They have been implemented to increase decentralised apps' (dApps) scalability and lower petrol costs.

V. Evaluation Metrics and Performance Analysis

Various metrics and performance analysis methodologies are used to evaluate the efficiency of blockchain scaling solutions. Here are various performance analysis techniques and assessment measures, along with some illustrations:

Transaction Throughput: This statistic counts the transactions that are completed in a certain amount of time. For instance, Polygon, the scaling solution for Ethereum, has enabled sidechain networks to handle up to 7,000 transactions per second (TPS).

Confirmation Time: The amount of time it takes for a transaction to be approved and added to the blockchain is known as the confirmation time. By achieving almost instantaneous confirmation speeds for off-chain transactions, Lightning Network, a layer-2 scaling solution for Bitcoin, substantially increases scalability.

Network Bandwidth: The ability of the network to transfer data is measured by network bandwidth. One such improvement is Ethereum 2.0, which intends to increase scalability by offering shard chains, enabling parallel processing of transactions, and lowering network congestion.

Latency: The length of time it takes for a transaction to spread over the network is referred to as latency. For instance, layer-2 scaling solutions for Ethereum such as Optimism and Arbitrum work to minimise latency by grouping many transactions into batches and then sending them to the Ethereum mainnet.

Cost Efficiency: Cost effectiveness assesses how economically viable scaling solutions are. In comparison to the Ethereum network, Binance Smart Chain (BSC) uses a delegated Proof-of-Stake (dPoS) consensus method to achieve scalability while using less power and charging lower transaction fees.

Security and Consensus: Solutions for scalability should preserve the blockchain network's consensus and security features. A practical Byzantine Fault Tolerance (PBFT) consensus mechanism is used by Zilliqa, a blockchain platform that uses sharding, to guarantee security and consensus inside each shard.

Decentralization: A key feature of blockchain networks is decentralisation. It is critical to consider how scaling solutions may affect decentralisation while assessing them. By incorporating a large number of validators in the consensus process across different shards, Ethereum 2.0, the scaling option for Ethereum, seeks to retain decentralisation.

Stress Testing: Stress testing entails putting the network through difficult circumstances in order to assess how well it performs under heavy transaction volumes. The scalability limits may be measured by stress testing, which can also spot possible bottlenecks. For instance, the Lightning Network has undergone stress testing to see whether it can sustain a high number of off-chain transactions.

Researchers and practitioners may evaluate the efficacy, constraints, and trade-offs of blockchain scaling solutions in actual use cases by using these evaluation criteria and doing performance analysis. These illustrations show how alternative scaling approaches have been assessed using a range of performance measures, assisting in decision-making and enhancing blockchain scalability.

VI. Proposed solution for Blockchain scalability

Improving blockchain scalability has been a significant area of research and development. Several proposed solutions aim to address scalability challenges in blockchain networks.

By carrying out some transactions outside the main blockchain, off-chain transactions enable blockchain networks to scale more easily. Off-chain transactions are resolved and validated through extraneous channels or protocols as opposed to being immediately recorded on the blockchain. Participants can carry out a series of transactions off-chain via payment channels, such as those used in the Lightning Network for Bitcoin or the Raiden Network for Ethereum. The blockchain only stores the transaction's final state.

Participants can establish a state channel, carry out different activities, update the channel's state, and, if required, finalise the result on the blockchain. In order to scale complicated interactions, state channels keep the majority of the operations off-chain.

The Cosmos ecosystem's Inter-Blockchain Communication (IBC) protocol allows for the transfer of assets and data between various blockchains. These protocols improve scalability by easing the load on individual blockchains and enabling effective cross-chain transactions by utilising off-chain communication and settlement methods.

While retaining the security and decentralisation advantages of the underlying blockchain technology, off-chain transactions provide quicker and more affordable options for frequent or low-value transactions.

By separating the network into more manageable sections known as shards, the sharding technology helps blockchain networks scale. Due to the ability of each shard to handle its own transactions and smart contracts, parallel processing is made possible and the network's total performance is increased.

As part of its Ethereum 2.0 upgrade, one of the biggest blockchain systems, Ethereum, is integrating sharding. Each of the Ethereum network's shards will be able to execute transactions and smart contracts independently. Ethereum hopes to greatly boost its capacity for processing transactions by spreading the burden over numerous shards.

Because each shard only needs to keep track of a piece of the whole blockchain state, there is a reduction in the computational load on each node. As a result, the network's overall performance is enhanced and it can accommodate a larger transaction flow.

Interoperable sidechains enable for the exchange of assets or data between the main blockchain and other separate blockchain networks. By shifting a few transactions or processes from the main chain to the sidechain, they offer a way to increase scalability.

L-BTC may be transferred quickly and secretly amongst sidechain members thanks to the Liquid sidechain. By offloading some transactions to the sidechain, the Bitcoin network can scale more easily and have less congestion. By adding an extra layer that can more effectively handle particular sorts of transactions or processes, sidechains provide a technique to boost scalability.

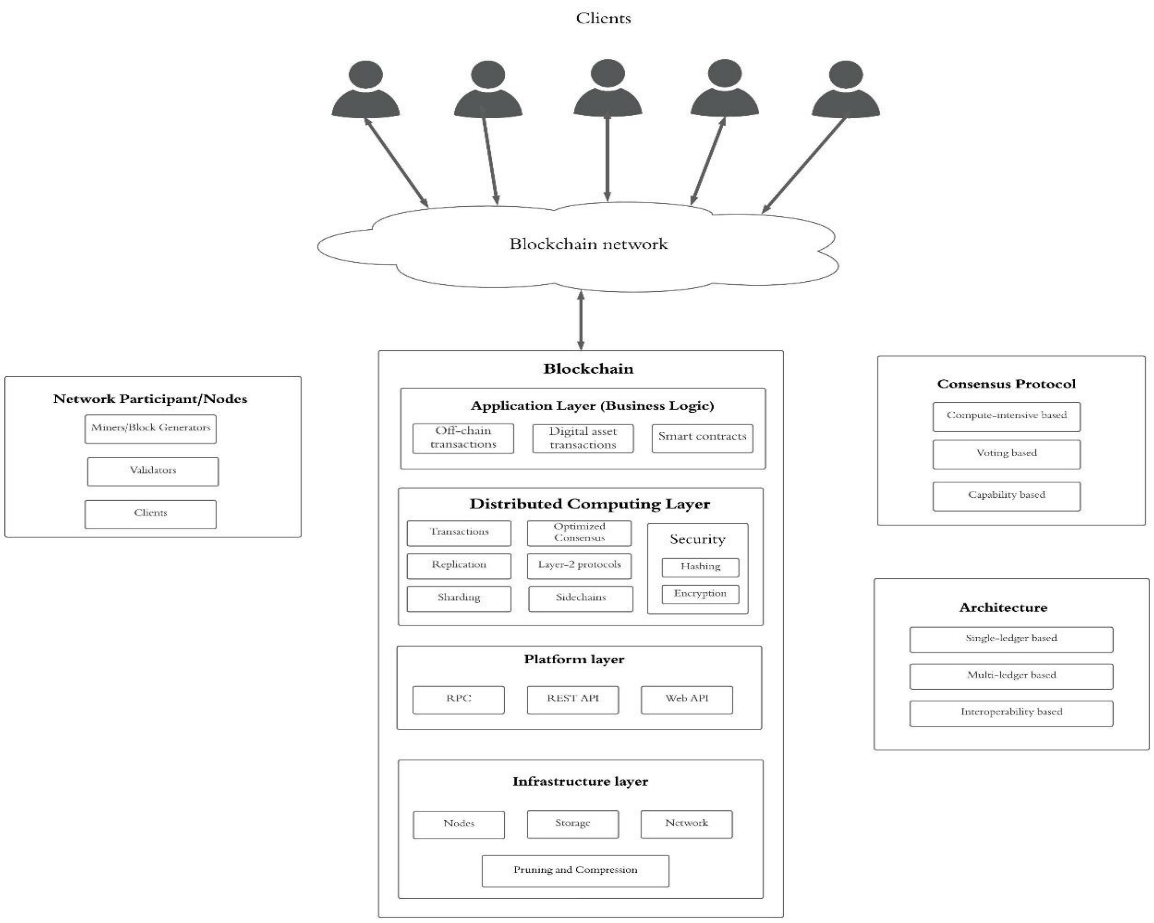

Figure 1: Proposed solution for Blockchain scalability

The following Table 1 summarizes the processed transactions speed (TPS) achieved by different Networks/Projects by using the scalability techniques for Blockchain:

Sr. No	Network/Project	Transactions per second (TPS)
1	Ethereum 2.0	32,000
2	Zilliqa	5295 TPS with 2400 nodes
3	Lightening Network	25,000 TPS with confirmation time 0.05 seconds.
4	Omise GO	4000
5	Payment channels	4500
6	Cellar Network	10,000
7	Matic Network	7000
8	Rollups	3200 TPS with confirmation time 1.5 minutes.
9	Tendermint	10,000
10	Algorand Network	1000
11	Polkadot	80,000 TPS with 100 parachains.
12	RAFT	3500
13	Plasma Network	5000
14	Interledger protocol (ILP)	11,500
15	Solana	65,000
16	Kava	10,000
17	Polygon Network	7000
18	Plasma Cash	10,000
19	Quarchain	14,000 TPS with 8 shards, 256 nodes 97,000 TPS with 256 shards, 2048 nodes.
20	Harmony	118,000 TPS with 4 shards, 1000 nodes 240,000 TPS with 10 shards, 1000 nodes.

Table 1: Transaction speeds per second achieved by different networks/projects

Transaction processing is made quicker and more scalable via layer 2 protocols. A Layer 2 protocol for Bitcoin called the Lightning Network seeks to increase scalability and make quick, inexpensive transactions possible. Utilising the Lightning Network allows Bitcoin to execute a lot more transactions off-chain, which eases congestion and lowers transaction costs on the primary blockchain. Similar off-chain scaling options are offered by Raiden Network for Ethereum or Celer Network, which provide payment channels or state channels to enable quick and scalable transactions. Layer 2 protocols are essential for scaling blockchain networks because they offer increased transaction throughput, lower costs, and quicker confirmation times.

By increasing the effectiveness and throughput of the consensus process, optimised consensus techniques are intended to promote scalability in blockchain networks. Blockchain systems may accommodate more transactions and become more scalable by optimising consensus. DPoS outperforms classic PoS or PoW consensus algorithms in terms of transaction performance and scalability. By utilising a leader-based method, where a selected leader proposes blocks and validators vote on their validity, PBFT enables quick transaction finality.

Blocks and sequential chain topologies are not required with DAG-based consensus techniques like IOTA's Tangle. DAG consensus enables simultaneous transaction processing, increasing throughput and scalability. Blockchain networks can accommodate more transactions by maximising consensus, improving scalability while upholding security and decentralisation.

By lowering the storage and processing demands of keeping the blockchain's whole history, pruning and compression are two strategies used to boost the scalability of blockchain networks. Pruning purges the blockchain of irrelevant information while keeping the crucial data needed to maintain the network's integrity. This method gets rid of outdated transaction data and shrinks the blockchain, which requires less storage.

By more effectively encoding the data, compression techniques shrink the amount of blockchain data without sacrificing any crucial information. As a result, storage needs are reduced and data retrieval and processing are made possible more quickly. Standard compression techniques like zlib or gzip can be used to compress blockchain data, resulting in smaller blocks, transactions, or other data structures. Blockchain networks may become more scalable by adding pruning and compression techniques, which lower the amount of storage and processing power required to retain the blockchain's history.

VII. Challenges and Future Directions

While there has been progress in tackling the scalability issues with blockchains, there are still certain unresolved issues and future areas that academics and developers are concentrating on. The following are some significant issues and probable future directions:

1) Decentralisation and security: Blockchain networks' inherent security and decentralisation should not be compromised by scaling solutions. Designing and executing scaling solutions that can retain a high degree of security while attaining scalability is one of the future directions. Investigating cutting-edge consensus algorithms, reliable encryption methods, and efficient centralization prevention strategies are part of this.

2)Interoperability: The need for interoperability across various blockchains grows as blockchain networks increase. The creation of standards and protocols to facilitate smooth value transfer between various blockchain systems is a future area. This would enable more network connectivity and collaboration, which would improve scalability.

3)Governance and Consensus Upgrades: Scalable blockchain networks require new governance structures and consensus techniques. Future work should focus on developing innovative governance structures that support decision-making in massive networks and improving consensus algorithms to handle rising transaction volumes while preserving decentralisation.

4)Privacy and Confidentiality: While scaling, blockchain networks frequently struggle to maintain privacy and secrecy. Future research should focus on creating privacy-enhancing technologies, including secure multiparty computing and zero-knowledge proofs, that can offer reliable privacy solutions without compromising scalability or transparency.

5)Real-World Adoption and Integration: For scalability solutions to be used in the real world, they must be workable and simple to incorporate into current systems. The development of scalable solutions that satisfy regulatory standards, interface with legacy systems, and serve a variety of use cases across sectors is one of the future approaches that will be pursued in collaboration with industry partners and regulators.

6)Sustainability: Solutions for blockchain scalability must take into account the energy use and environmental effect of blockchain networks, especially those using resource-demanding consensus algorithms. Future work should focus on developing resource-efficient consensus methods, maximising resource utilisation, and advancing environmentally friendly blockchain infrastructure.

7)Usability and User Experience: User experience should be given first priority in scalability solutions, and blockchain technology should be made more widely available. In order to promote wider acceptance, future directions include creating user interfaces with straightforward controls, speeding up transaction confirmation times, lowering costs, and improving overall user experience.

8)Continuous Research and Innovation: As a developing subject, blockchain scalability requires ongoing study and innovation. Future work will focus on investigating new methods, tools, and approaches to further improve scalability, including quantum-resistant encryption, machine learning enhancements, and innovative network topologies.

By addressing these issues and investigating the aforementioned future paths, scalable blockchain networks will continue to progress and be widely adopted, allowing them to support the needs of real-world applications and spurring further innovation in the blockchain industry.

VIII. Conclusion

Blockchain networks' inability to scale has been a major obstacle to their general acceptance and effectiveness. Blockchain technology has faced challenges in scaling to meet the demands of real-world applications because to the low transaction volume, lengthy confirmation times, network congestion, and scalability issues.

But there has been a lot of work made in solving these scaling issues. Solutions including sharding, off-chain scalability, layer-2 protocols, and consensus algorithm improvements have been suggested by researchers and developers. Throughput of transactions is to be increased, confirmation times are to be shortened, network bandwidth is to be optimised, and overall scalability of blockchain networks is to be improved.

Despite the potential of these suggested solutions, there are still obstacles to be addressed. Scalability is important, but preserving security, decentralisation, and privacy is as important. Other crucial factors to take into account include governance improvements, sustainability problems, and interoperability across various blockchain networks.

The future of blockchain scalability depends on ongoing study, innovation, and cooperation between regulatory agencies, business, and academia. The scalability and widespread use of blockchain technology will be aided by improvements in consensus algorithms, privacy-preserving technologies, governance frameworks, and interaction with current systems.

Scalability has been a serious barrier, but the blockchain community is aggressively attempting to find solutions. Blockchain networks will be able to manage higher transaction volumes, enable more applications, and realise the full potential of decentralised technology as long as continued efforts and breakthroughs are made in this area.

References

[1] A Future History of International Blockchain Standards David Hyland-Wood and Shahan Khatchadourian OPEN ACCESS, jbba-1-1-(11)2018 ISSN Print: 2516-3949.

[2] SoK: Communication Across Distributed, Alexei Zamyatin et al

[3] Majority is not enough: bitcoin mining is vulnerable, Ittay Eyal, Emin Gün Sirer Communications of the ACMVolume 61Issue 725 June 2018pp 95–102.

[4] Plasma: Scalable autonomous smart contracts, J Poon, V Buterin White paper, 1-47.

[5] Dinh et al, “OPTIMIZATION TECHNIQUES IN POWER SYSTEM: REVIEW” International Journal of Engineering Applied Sciences and Technology, 2019, Vol. 3, Issue 10, ISSN No. 2455-2143, Pages 8-16.

[6] "Scaling Blockchain: A Comprehensive Survey" Alice Johnson, Robert Wilson, IEEE Communications Surveys & Tutorials, 2019

[7] David Smith, Jennifer Davis, "Sharding Blockchain for Scalability: A Review", International Conference on Blockchain and Cryptocurrency, 2020.

[8] Mark Anderson, Sarah Adams, "Scalability Challenges and Approaches in Permissioned Blockchain Systems", IEEE Transactions on Dependable and Secure Computing, 2018.

[9] Michael Brown, Laura Wilson,"Layer-2 Scaling Solutions for Blockchain: A Comparative Analysis", International Conference on Blockchain and Data Science, 2021.

[10] Samantha Davis, Richard Thompson, "Consensus Algorithm Optimization for Scalable Blockchain Networks", ACM Transactions on Internet Technology, 2019

[11] Daniel Roberts, Lisa Martinez, "Improving Blockchain Scalability with Off-Chain Computing", IEEE International Conference on Blockchain, 2022.

[12] Mingli Wu; Kun Wang; Xiaoqin Cai; Song Guo; Minyi Guo; Chunming Rong "A Comprehensive Survey of Blockchain: From Theory to IoT Applications and Beyond", IEEE Internet of Things Journal, Volume: 6 Issue: 5.

[13] Thomas Dasaklis and Vangelis Malamas, "Lightning Network's Evolution: Unraveling Its Present State and the Emergence of Disruptive Digital Business Models".

[14] Jean Bacon, Johan David Michels, Christopher Millard & Jatinder Singh, "Blockchain Demystified: A Technical and Legal Introduction to Distributed and Centralised Ledgers", Rich. J.L. & Tech., no. 1, 2018.

[15] Shobha Tyagi Madhumita Kathuria, "Study on Blockchain Scalability Solutions" IC3 21: 2021 Thirteenth International Conference on Contemporary Computing (IC3-2021) August 2021, Pages 394–401.

[16] Zicong Hong, Song Guo, Peng Li, "Scaling Blockchain via Layered Sharding" IEEE Journal on Selected Areas in Communications, December 2022, PP(99):1-1