A Blockchain Review based on the Scalability Trilemma

Carlos Melo, Glauber Gonçalves, Francisco A. Silva, and André Soares
Universidade Federal do Piauí (UFPI), Picos - PI, Brazil
{casm, ggoncalves, faps, andre.soares}@ufpi.edu.br

***Abstract*—Blockchain technology emerged from not-so-new concepts such as cryptography and distributed systems. However, are blockchain-based applications suitable to replace traditional distributed applications? Performance evaluation can help us to achieve an answer to this question. This paper assesses the current state-of-the-art performance evaluation in some of the most popular platforms that provide public, private, or cross-operation blockchain-based applications. We highlight key studies, technologies, and metrics focusing on three main research aspects: (i) Scalability, (ii) Security, and (iii) Interoperability. Some of the key obtained results point out that works regarding interoperability are an important gap in the blockchain performance field. Hyperledger Fabric and Ethereum are among the most prominent platforms, meaning that academics and industry need to explore other platforms. Finally, we discovered that measurement was the most used performance evaluation method, and it mainly focused on transaction latency and throughput.**

***Index Terms*—Performance, Security, Scalability, Interoperability, Blockchain**

I. Introduction

Blockchain surpassed the payment system concept and evolved into a comprehensive platform model that can host diverse distributed services (1). Moreover, as blockchain-based technologies evolve, extensive efforts have been devoted to assessing their feasibility and determining if this paradigm rooted in traditional tools like cryptography and distributed computing can replace conventional databases and similar systems. Many researchers use performance evaluation as a tool that may help us find an answer to these open questions.

This paper addresses blockchain performance, and as its main contributions, comprehensively identifies the current state-of-the-art in this field, mainly concerning three key research questions: scalability, security, and interoperability. It aims to fill gaps in the existing literature by offering novel insights into the relationship between these factors, considering the dynamic nature of blockchain-based technologies, and pointing out challenges and opportunities.

The remainder sections of this paper are structured as follows. Section II delves into the evaluation of system performance. Section III details the research questions this review aims to answer. Section IV provides a comprehensive overview of some of the most prominent blockchain platforms. Section V presents the conclusive findings of the review, encompassing platforms, metrics and the nature of the conducted evaluations. Considerable challenges and opportunities identified by this review are outlined in Section VI. Lastly, Section VII encapsulates conclusions and final remarks.

II. Background

A. Blockchain

A blockchain application relies upon shared ledgers for storing transaction records within entities known as blocks. These blocks are systematically inserted into the ledger and retain data about the performed transactions. Figure 1 presents a blockchain's typical operation.

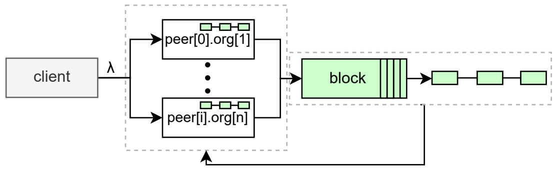

Fig. 1: How Does Blockchain Work?

Client transactions (λ) are directed towards a peer-to-peer network comprising a set of machines called nodes. These machines undertake the execution and validation process for the given transactions. Furthermore, an ordering process can be integrated into the workflow (2). Each transaction is integrated into a block alongside other transactions, each block is appended or persisted. Typically, each node possesses a copy of the blockchain. Based on this, most blockchain's performance evaluation studies focus on:

- How long does a transaction take to be persisted?
- What is the blockchain's throughput?
- How many computational resources are required to perform these transactions?
- How does the resource utilization scale?

B. Performance Evaluation

Performance evaluation involves the assessment and analysis of a specific system under test (SUT) (3). The **SUT** usually encompasses all the specific hardware, software, networks, and configurations required for the execution and maintenance of the system (2).

Most performance evaluation studies rely on a **Test Harness**, a set of clients for sending transactions and collecting observations of the (SUT) (2). Figure 2 provides an overview of the performance evaluation process.

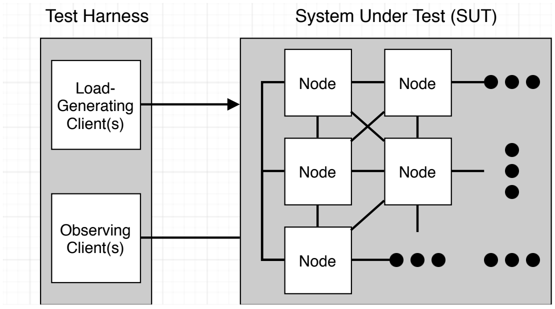

Fig. 2: Performance Evaluation Methodology

C. Performance Metrics

When assessing the performance, three primary metrics are commonly evaluated: Throughput, Latency, and Resource Utilization. The **throughput** refers to the rate at which successful jobs are performed within a specific time (3). In the context of blockchain, the focus is primarily on transaction throughput, and the commonly used metric is the number of transactions per second (tps) (2).

$$\texttt{Throughput} = \frac{\texttt{Sum of successful jobs}}{\texttt{time}} \tag{1}$$

The **latency** refers to the time it takes for a transaction to be confirmed and included in the blockchain (2). It represents the delay between when a user submits a transaction and its final confirmation. Therefore, latency is a user-perspective metric. Lower latency usually indicates faster transaction processing, which is highly desirable for real-time applications.

Latency also encompasses the **mean response time** (MRT). MRT represents the system's total duration to process a transaction or job. It can be calculated by summing the latencies of all transactions within a specific period and dividing it by the number of transactions within that period(3).

$$\texttt{MRT} = \frac{\texttt{Sum of Latencies for a period}}{\texttt{Number of Transactions in that period}} \tag{2}$$

Another important latency-related metric is the **consensus time** (4), which measures the time required for the network to reach a consensus on a specific block or set of transactions. Consensus time may include the propagation of transactions among nodes, their validation, and the agreement on their inclusion in the blockchain.

The **resource utilization** metrics usually focus on monitoring the queue size or capacity of a device and how much CPU, storage (disk), and RAM is being used during transaction processing (5). For example, in (1), the authors identified that the disk could become a bottleneck in smaller infrastructures, significantly impacting both throughput and latency, particularly during write operations such as committing a new block.

Another closely related metric is the transaction **discard rate**, which encompasses the set of transactions that could not be processed due to resource limitations or network connectivity issues within a given period.

D. Modeling and Simulation

A model is an abstraction of a real system (3). In general, two types of scientific models are used to evaluate shared resource systems: analytical models and simulation models (3).

Analytical models consist of formulas and computational algorithms that provide desired values for a system's performance metrics based on input parameters. On the other hand, simulation models consist of computer programs that execute or simulate activities similar to the real system (3).

Simulation models are generally more costly to develop than analytical models, raising questions about their feasibility concerning implementing the real system or a prototype. However, analytical models have lower accuracy but offer a better cost-benefit ratio in their development.

III. Research Questions

A. Scalability Trilemma

The Scalability Trilemma, often referred to as the Buterin Trilemma, embodies the challenge of balancing **security** and **decentralization** against the **scalability** of distributed systems.

Security is essential to maintain user trust, prevent fraudulent activities, and uphold the platform's reliability and performance. However, a robust consensus protocol, such as a proof-of-work (PoW) employed by Bitcoin, may directly and negatively impact the overall system performance regarding throughput and latency but increases the decentralization capabilities (6).

The **decentralization** level within a system has an inverse relationship with its performance in terms of throughput (transactions per second) and latency. This trade-off is particularly noticeable in public blockchains like Bitcoin, where increased decentralization often results in reduced performance, underscoring the inherent challenge of the Scalability Trilemma.

The **scalability** refers to the platform's capacity to handle a growing number of transactions while maintaining efficiency, which means low latency and high throughput (4). Typically, scalability assessment involves analyzing how the system's performance and throughput (transactions per second) are affected as the workload increases. This analysis helps determine the platform's ability to grow in size and complexity while sustaining optimal performance.

Public blockchain platforms like Bitcoin network may reach up to 5 transactions per secondm while the Ethereum typically achieve throughputs of up to 100 transactions per second. In contrast, permissioned and private networks, such as Hyperledger Fabric, report throughputs reaching up to 3,000 transactions per second (7).

Interoperability allows for enhancing transaction throughput from the perspective of a public blockchain. For instance, a private or permissioned blockchain can handle activities that might be time-consuming on a public blockchain, such as transaction endorsement or validation. Figure 3 depicts the trilemma and emphasizes interoperability as a key mechanism.

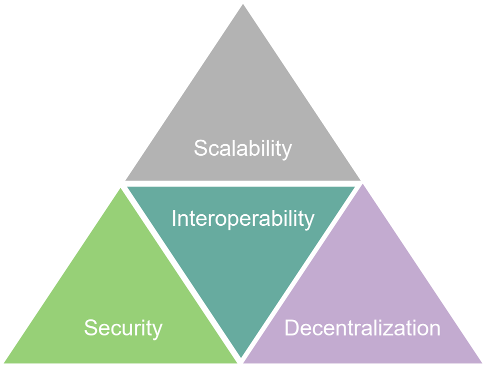

Fig. 3: Interoperability + Scalability Trilemma

IV. Comparison between platforms and consensus

The Hyperledger Working Group released a white paper (2) that compares the prevalent consensus protocols employed by mainstream platforms. Figure 4 depicts a radar plot that compares the speed of throughput (transactions per second), scalability, and finality.

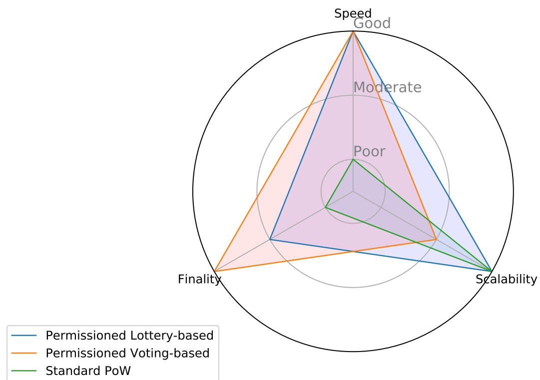

Fig. 4: Comparison between consensus approaches

The performance level was categorized into poor, moderate, and good. Public blockchains based on Proof-of-Work (PoW) protocols, such as the Bitcoin network, exhibit good scalability, allowing numerous nodes to join and leave without adversely affecting the system's performance metrics. However, PoW protocols have limited speed and finality, as transactions may take hours due to the consensus protocol, which also demands transaction fees from the client's perspective.

On the other hand, permissioned networks handle more transactions since they operate within a controlled environment with fewer nodes. However, permissioned lottery-based protocols like Proof-of-Elapsed-Time (PoET) have a moderate level of finality, as multiple winners may be selected, leading to conflicts between nodes and blocks.

Meanwhile, permissioned voting-based protocols such as Practical Byzantine Fault Tolerance (PBFT), Proof-of-Authority (PoA), and Kafka exhibit moderate scalability. Increasing the number of nodes in such protocols can have a detrimental impact, resulting in reduced speed and finality.

V. Results

The data was collected after defining a search string: **"performance" AND "blockchain" AND ("scalability" OR "interoperability" OR "security")**, and the data range considered papers published between 2017 and 2023.

After data collection, the initial step involved applying filters to identify relevant papers based on their title, abstract, and nature. This initial analysis narrowed our focus to peer-reviewed publications. Other sources such as thesis, reports, white papers, book chapters, pre-printed and working papers were excluded.

As a result, we began with 86 relevant publications and refined it to 53 research. Subsequently, we sought to obtain these remaining publications to conduct a thorough examination. However, it should be noted that three publications were unavailable, leaving us with 50 publications.

Our assessment of these 50 publications considered various aspects, including the publication year, the blockchain platform, the evaluation method employed, the performance metrics, and the extent to which the publication addressed at least one of our research questions.

Among the 50 publications, ten were excluded during the comprehensive reading phase as they did not evaluate performance metrics or provide a discussion related to performance. The remaining 40 publications, which established a clear link between performance evaluation and our three research questions, were further analyzed. Among these, four solely focused on evaluating performance metrics without explicitly addressing the research questions.

A. *Research Questions*

Most publications (19) concentrate exclusively on performance and scalability issues, while 7 emphasize the intersection of performance and security concerns—additionally, two publications center solely on interoperability aspects.

As the least evaluated research criteria, interoperability highlights a path that needs to be taken to extend the blockchain state of the art. Public blockchains tend to be slower than private and permissioned environments. However, they use powerful consensus algorithms that enable security against malicious agents and a trade-off related to the costs of maintaining a private infrastructure capable of performing the given transactions. (8) and (9) solely evaluated interoperability and presented us with means to improve the performance of the blockchain types.

Certain publications addressed more than one research question, with two evaluating all three. In (10), the authors evaluated and compared blockchain technology with the current service provider model (client/server) within a healthcare data management system. Similarly, (11) introduced a novel cryptographic construction known as anonymous multi-hop lock (AMHL), which facilitates secure, interoperable, and privacy-preserving payment-channel networks (PCNs).

B. Evaluated Metrics

Among the evaluated papers, throughput emerged as the most prominent metric. Fourteen publications assessed this metric, while other significant performance metrics included latency, resource consumption/utilization, and derived metrics such as response time.

In (1), the authors examined the impact of resource consumption on the throughput, latency, and overall system availability of the Hyperledger Fabric platform. Additionally, (7) conducted an extensive empirical study of the Hyperledger Fabric blockchain platform and provided guidelines for parameter configuration to maximize transaction throughput. Similarly, (12) proposed a repeatable methodology for evaluating blockchain platforms, focusing on both throughput and latency, and evaluated the performance of Hyperledger Fabric and Ethereum using this approach.

C. Evaluation Method

The most prevalent evaluation method is the measurement through experimentation. Among the evaluated papers, 44% used modeling and measurement, 38% used solely measurement, 8% used modeling and simulation, 5% solely modeling, and the same 5% opted for simulation only.

(13) introduced the Blockbench tool, enabling throughput and latency evaluation for Ethereum and other prominent blockchain platforms. The authors also conducted an in-depth survey of blockchain systems, categorizing them based on essential technical concepts, and provided an experiment to demonstrate the feasibility of their proposed tool.

In other publications, such as (14), the authors performed experiments to investigate the impact of blockchain network workloads on the performance of Hyperledger Fabric. Similarly, (15) evaluated the performance of a novel m-commerce application called MobiChain through experiments, focusing on mining time and resource consumption, particularly regarding energy aspects. Furthermore, (16) established a multi-node blockchain using Ethereum in a private network and implemented an e-voting application using smart contracts.

In (17; 18; 19; 20; 21), the authors employed probability models as mathematical representations based on throughput and latency formulas to assess the performance of Hyperledger Fabric or Ethereum blockchain platforms. These papers primarily focused on analyzing the scalability of the systems. Probability models can be classified as either analytical or numerical models. Thus, these papers fall into the broader category of models.

D. Evaluated Blockchain Platform

Most publications concentrated on platforms capable of providing a private or permissioned environment. This preference is attributed to the fact that performance data and values of public blockchains are already publicly available. Moreover, private and permissioned blockchains offer greater control over the environment, enabling researchers to identify issues, bottlenecks, and opportunities within a specific platform.

Hyperledger Fabric has gained considerable recognition and has been the platform of choice for many research papers, particularly in the scalability study, as demonstrated in (22). Other papers have focused on addressing security concerns, such as (23; 24), and exploring the potential of blockchain technology to enhance healthcare systems, like (25).

It should be noted that certain publications have specifically evaluated consensus protocols that can be applied to multiple blockchain platforms, as highlighted in (26; 27; 28; 29). Among these evaluations, the Practical Byzantine Fault Tolerance (PBFT) protocol has been extensively studied, particularly in the context of Hyperledger Fabric.

Lastly, Table I comprehensively compares the remaining papers based on the platforms examined, evaluation methods employed, and performance metrics considered.

TABLE I: Comparison between evaluated works

Paper	RQs	Platforms	Metrics	Method
(12)	1	Ethereum and HF	TPS and Latency	Measurement
(4)	1	HF	Latency	Modeling and Measurement
(29)	1	Protocols	TPS and Response Time	Modeling and Measurement
(13)	1	Ethereum and HF	TPS and Latency	Measurement
(7)	1	HF	TPS and Latency	Measurement
(30)	1, 3	HF	TPS and Latency	Measurement
(28)	2, 3	Protocols and HF	TPS and Latency	Simulation
(15)	1, 3	Mobichain	TPS and Latency	Measurement
(20)	3	Rainbowchain	TPS	Modeling and Measurement
(11)	1, 2, 3	Original	Computation Time	Modeling and Measurement
(8)	2	Ethereum and Bitcoin	RU	Measurement
(9)	2	Original	TPS, Latency, Retransmissions	Measurement
(31)	1	HF	TPS, Latency and RU	Modeling and Measurement
(24)	3	HF	TPS and Latency	Measurement
(32)	1, 3	Ethereum and HF	TPS and Latency	Simulation
(33)	3	Original	TPS	Modeling and Simulation
(14)	1	HF	TPS	Measurement
(34)	1	Ethereum	Success Probability	Modeling and Simulation
(35)	1, 2	Original	TPS, Latency and RU	Modeling and Measurement
(21)	1	Ethereum	TPS	Modeling and Measurement
(36)	1	HF	TPS and Latency	Modeling and Measurement
(37)	1	Multichain	TPS and Latency	Measurement
(18)	1	HF	TPS and Latency	Modeling and Measurement
(25)	1	HF	TPS	Modeling and Measurement
(5)	1	Ethereum	TPS, Latency, RU and Energy	Measurement
(16)	1	Ethereum	TPS and Latency	Measurement
(10)	1, 2, 3	Original	TPS and RU	Modeling and Measurement
(38)	3	Original	TPS, Integrity and RU	Modeling
(39)	2, 3	Protocols	TPS, Integrity and Latency	Modeling
(22)	1	HF	TPS and Latency	Measurement
(17)	1	HF	TPS and Latency	Modeling and Measurement
(19)	1	HF	Latency	Modeling and Measurement
(1)	1	HF	TPS, Latency and RU	Modeling and Measurement
(40)	1	HF	Latency	Modeling and Measurement
(26)	1	Protocols	TPS and Consensus Time	Modeling and Simulation
(23)	3	HF	TPS, RU and Endorsement Time	Modeling and Measurement

RQs 1, 2, and 3 represent scalability, interoperability, and security. HF - Hyperledger Fabric, TPS - Throughput, and RU - Resource Utilization.

VI. Challenges and Opportunities

Numerous studies have focused on enhancing the performance of blockchain technology by considering key metrics such as transaction throughput, network latency, scalability, and response time. However, relatively few attempts have demonstrated the feasibility of adopting blockchain technology over traditional distributed databases. Generally, traditional databases outperform most blockchain-based technologies. For instance, the VISA payment platform processes over 65,000 transactions per second and serves a user base of over 3 billion credit card holders. These figures far surpass those achieved by any public blockchain platform. Nevertheless, among the prominent private and permissioned environments, the VISA payment system lags behind Hyperledger Fabric utilizing the Kafka consensus mechanism.

Developers and researchers acknowledge that the trade-off between performance and security is one of the primary factors limiting blockchain's superiority over traditional distributed databases in terms of performance. They argue that security holds equal or even greater importance than performance in times like the present. It is expected that if a payment system, which is just one application in the realm of blockchain, faces performance limitations, the same can occur for other applications requiring high throughput. Permissioned and private blockchain platforms emerged from this perspective. However, they often conflict with one of the fundamental principles behind blockchain technology: the absence of a central authority coordinating an application or environment.

VII. Conclusion and Final Remarks

This survey provides an in-depth analysis of the current state-of-the-art in performance evaluation of blockchain platforms, specifically focusing on three key research questions derived from the scalability trilemma. We identified the most commonly evaluated metrics: throughput, latency, and resource utilization.

Scalability has been the primary focus of most evaluated papers, while interoperability has received less attention. Experimentation has emerged as the most frequently employed evaluation method, followed closely by probability, analytical, and numerical models.

Threrefore, this study provides a comprehensive overview of performance evaluation in blockchain technologies, highlighting fundamental metrics and key platforms.

By understanding the complexities of performance evaluation in blockchains, this study offers valuable insights for researchers, professionals, and decision-makers. The identified opportunities and challenges provide a solid foundation for advancing research and effectively implementing blockchain-based solutions.

References

[1] C. Melo, F. Oliveira, J. Dantas, J. Araujo, P. Pereira, R. Maciel, and P. Maciel, "Performance and availability evaluation of the blockchain platform hyperledger fabric," *The Journal of Supercomputing*, vol. 78, no. 10, pp. 12 505–12 527, 2022.

[2] Hyperledger, "Hyperledger blockchain performance metrics white paper," Hyperledger Foundation, Tech. Rep., 2018.

[3] P. R. M. Maciel, *Performance, reliability, and availability evaluation of computational systems, volume I: performance and background*. CRC Press, 2023.

[4] H. Sukhwani, J. M. Martínez, X. Chang, K. S. Trivedi, and A. Rindos, "Performance modeling of pbft consensus process for permissioned blockchain network (hyperledger fabric)," in *2017 IEEE 36th Symposium on Reliable Distributed Systems (SRDS)*. IEEE, 2017, pp. 253–255.

[5] S. Misra, A. Mukherjee, A. Roy, N. Saurabh, Y. Rahulamathavan, and M. Rajarajan, "Blockchain at the edge: Performance of resource-constrained iot networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 32, no. 1, pp. 174–183, 2020.

[6] D. Li, C. Jiang, Y. Liu, L. Tang, and L. Yan, "A survey on security and performance optimization of blockchain," in *Communications and Networking: 15th EAI International Conference, ChinaCom 2020, Shanghai, China, November 20-21, 2020, Proceedings*. Springer, 2021, pp. 101–111.

[7] P. Thakkar, S. Nathan, and B. Viswanathan, "Performance benchmarking and optimizing hyperledger fabric blockchain platform," in *2018 IEEE 26th International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*. IEEE, 2018, pp. 264–276.

[8] T. Jiang, H. Fang, and H. Wang, "Blockchain-based internet of vehicles: distributed network architecture and performance analysis," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 4640–4649, 2018.

[9] H. Jin, X. Dai, and J. Xiao, "Towards a novel architecture for enabling interoperability amongst multiple blockchains," in *2018 IEEE 38th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2018, pp. 1203–1211.

[10] L. Ismail, H. Hameed, M. AlShamsi, M. AlHammadi, and N. AlDhanhani, "Towards a blockchain deployment at uae university: Performance evaluation and blockchain taxonomy," in *Proceedings of the 2019 International Conference on Blockchain Technology*, 2019, pp. 30–38.

[11] G. Malavolta, P. Moreno-Sanchez, C. Schneidewind, A. Kate, and M. Maffei, "Anonymous multi-hop locks for blockchain scalability and interoperability," *Cryptology ePrint Archive*, 2018.

[12] S. e. a. Pongnumkul, "Performance analysis of private blockchain platforms in varying workloads," in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*. IEEE, 2017, pp. 1–6.

[13] T. T. A. Dinh, J. Wang, G. Chen, R. Liu, B. C. Ooi, and K.-L. Tan, "Blockbench: A framework for analyzing private blockchains," in *Proceedings of the 2017 ACM International Conference on Management of Data*, 2017, pp. 1085–1100.

[14] M. Kuzlu, M. Pipattanasomporn, L. Gurses, and S. Rahman, "Performance analysis of a hyperledger fabric blockchain framework: Throughput, latency and scalability," in *2019 IEEE International Conference on Blockchain (Blockchain)*. IEEE, 2019, pp. 536–540.

[15] K. Suankaewmanee, D. T. Hoang, D. Niyato, S. Sawadsitang, P. Wang, and Z. Han, "Performance analysis and application of mobile blockchain," in *2018 international conference on computing, networking and communications (ICNC)*. IEEE, 2018, pp. 642–646.

[16] P. M. Dhulavvagol, V. H. Bhajantri, and S. Totad, "Blockchain ethereum clients performance analysis considering e-voting application," *Procedia Computer Science*, vol. 167, pp. 2506–2515, 2020.

[17] M. Nischwitz, M. Esche, and F. Tschorsch, "Bernoulli

meets pbft: Modeling bft protocols in the presence of dynamic failures," in *2021 16th Conference on Computer Science and Intelligence Systems (FedCSIS)*. IEEE, 2021, pp. 291–300.

[18] D. Krishnaswamy, "Performance considerations for edge blockchain systems in emerging 5g data networks," in *Proceedings of the 21st International Conference on Distributed Computing and Networking*, 2020, pp. 1–6.

[19] X. Xu, G. Sun, L. Luo, H. Cao, H. Yu, and A. V. Vasilakos, "Latency performance modeling and analysis for hyperledger fabric blockchain network," *Information Processing & Management*, vol. 58, no. 1, p. 102436, 2021.

[20] S. Kim, "Impacts of mobility on performance of blockchain in vanet," *IEEE Access*, vol. 7, pp. 68 646–68 655, 2019.

[21] I. Weber, Q. Lu, A. B. Tran, A. Deshmukh, M. Gorski, and M. Strazds, "A platform architecture for multi-tenant blockchain-based systems," in *2019 IEEE International Conference on Software Architecture (ICSA)*. IEEE, 2019, pp. 101–110.

[22] L. Hang and D.-H. Kim, "Optimal blockchain network construction methodology based on analysis of configurable components for enhancing hyperledger fabric performance," *Blockchain: Research and Applications*, vol. 2, no. 1, p. 100009, 2021.

[23] A. La Salle, A. Kumar, P. Jevtić, and D. Boscovic, "Joint modeling of hyperledger fabric and sybil attack: Petri net approach," *Simulation Modelling Practice and Theory*, vol. 122, p. 102674, 2023.

[24] G. G. R. Roy and S. B. R. Kumar, "A security framework for a sustainable smart ecosystem using permissioned blockchain: performance evaluation," *Int. J. Innov. Technol. Explor. Eng.*, vol. 8, no. 10, pp. 4247–4250, 2019.

[25] S. Tanwar, K. Parekh, and R. Evans, "Blockchain-based electronic healthcare record system for healthcare 4.0 applications," *Journal of Information Security and Applications*, vol. 50, p. 102407, 2020.

[26] W. N. Suliyanti and R. F. Sari, "Blockchain-based double-layer byzantine fault tolerance for scalability enhancement for building information modeling information exchange," *Big Data and Cognitive Computing*, vol. 7, no. 2, p. 90, 2023.

[27] D. Huang, X. Ma, and S. Zhang, "Performance analysis of the raft consensus algorithm for private blockchains," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 1, pp. 172–181, 2019.

[28] G. Sagirlar, B. Carminati, E. Ferrari, J. D. Sheehan, and E. Ragnoli, "Hybrid-iot: Hybrid blockchain architecture for internet of things-pow sub-blockchains," in *2018 IEEE International Conference on Internet of Things (iThings)*. IEEE, 2018, pp. 1007–1016.

[29] J. Spasovski and P. Eklund, "Proof of stake blockchain: performance and scalability for groupware communications," in *Proceedings of the 9th International Conference on Management of Digital EcoSystems*, 2017, pp. 251–258.

[30] O. Alphand, M. Amoretti, T. Claeys, S. Dall'Asta, A. Duda, G. Ferrari, F. Rousseau, B. Tourancheau, L. Veltri, and F. Zanichelli, "Iotchain: A blockchain security architecture for the internet of things," in *2018 IEEE wireless communications and networking conference (WCNC)*. IEEE, 2018, pp. 1–6.

[31] H. Sukhwani, N. Wang, K. S. Trivedi, and A. Rindos, "Performance modeling of hyperledger fabric (permissioned blockchain network)," in *2018 IEEE 17th International Symposium on Network Computing and Applications (NCA)*. IEEE, 2018, pp. 1–8.

[32] M. Liu, F. R. Yu, Y. Teng, V. C. Leung, and M. Song, "Performance optimization for blockchain-enabled industrial internet of things (iiot) systems: A deep reinforcement learning approach," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 6, pp. 3559–3570, 2019.

[33] Y. Sun, L. Zhang, G. Feng, B. Yang, B. Cao, and M. Imran, "Performance analysis for blockchain driven wireless iot systems based on tempo-spatial model," in *2019 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC)*. IEEE, 2019, pp. 348–353.

[34] Y. J. Kim and C. S. Hong, "Blockchain-based node-aware dynamic weighting methods for improving federated learning performance," in *2019 20th Asia-Pacific Network Operations and Management Symposium (APNOMS)*. IEEE, 2019, pp. 1–4.

[35] A. Roehrs, C. A. da Costa, R. da Rosa Righi, V. F. da Silva, J. R. Goldim, and D. C. Schmidt, "Analyzing the performance of a blockchain-based personal health record implementation," *Journal of biomedical informatics*, vol. 92, p. 103140, 2019.

[36] P. Yuan, K. Zheng, X. Xiong, K. Zhang, and L. Lei, "Performance modeling and analysis of a hyperledger-based system using gspn," *Computer Communications*, vol. 153, pp. 117–124, 2020.

[37] K. M. Khan, J. Arshad, and M. M. Khan, "Investigating performance constraints for blockchain based secure e-voting system," *Future Generation Computer Systems*, vol. 105, pp. 13–26, 2020.

[38] Z. Cui, X. Fei, S. Zhang, X. Cai, Y. Cao, W. Zhang, and J. Chen, "A hybrid blockchain-based identity authentication scheme for multi-wsn," *IEEE Transactions on Services Computing*, vol. 13, no. 2, pp. 241–251, 2020.

[39] Y. Wu, P. Song, F. Wang *et al.*, "Hybrid consensus algorithm optimization: A mathematical method based on pos and pbft and its application in blockchain," *Mathematical Problems in Engineering*, vol. 2020, 2020.

[40] S. Lee, M. Kim, J. Lee, R.-H. Hsu, M.-S. Kim, and T. Q. Quek, "Facing to latency of hyperledger fabric for blockchain-enabled iot: Modeling and analysis," *IEEE Network*, 2023.