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Decentralized E-Voting Anonymity and Scalability via Parallel Differential Privacy on Hyperledger Besu

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Abstract- Blockchain - based e-voting systems use decentralized ledgers to securely record encrypted votes, ensuring immutability, transparency, and tamper-proof verification without central authorities. These systems such as the existing BP-Vot framework integrate smart contracts, k,ε-differential privacy, and self-sovereign identities (SSI) to balance transparency, security, and voter anonymity in remote elections. BP-Vot deploys on Hyperledger Besu, using a single pivot candidate to redistribute votes probabilistically (θ=1/d), achieving 98%+ vote approximation accuracy via Min-Max regression and 1s/TX latency—24% better than prior art—while proving robustness against reconstruction attacks. However, limitations include single-pivot privacy fragility in low- volume elections, partial reliance on election authority for key registration, and untested scalability beyond 50k votes or additional nodes.This work proposes a multi-pivot parallel differential privacy extension, dynamically selecting multiple pivots for distributed noise injection, fully integrated with SSI Web3 wallets and immutable contracts. Benefits encompass superior anonymity for millions of votes, eliminated centralization risks, and optimized performance for national-scale deployments. Evaluations confirm linear privacy/accuracy gains with vote volume, independent of candidate count, enabling GDPR-compliant, trustless e-voting superior to state-of-the-art.

Keywords: Blockchain, e-voting systems, decentralized ledgers, BP-Vot framework, Hyperledger Besu, Min-Max regression, SSI Web3 wallets

I. INTRODUCTION

Blockchain-based e-voting systems use decentralized ledgers to store encrypted votes that are immutable, transparent, and tamper-evident without the need for central authorities. Examples of blockchain-based e-voting systems include the existing BP-Vot framework, which utilizes smart contracts, k,ε-differential privacy, and self-sovereign identities to maintain transparency, security, and voter anonymity in remote elections. BP-Vot is deployed on Hyperledger Besu and uses a single pivot candidate to probabilistically redistribute votes (θ=1/d) and achieves over 98% vote approximation accuracy through Min-Max regression and a 1s/TX latency, which represents a 24% improvement over previous methods while also being resistant to reconstruction attacks. Nevertheless, challenges remain, such as the vulnerability of single-pivot privacy in low-volume elections, the need for some parts of the system to still rely on election authorities for key registration, and the lack of scalability testing with more than 50,000 votes or additional nodes. To address these limitations, this work proposes a multi-pivot parallel differential privacy extension that dynamically selects several pivots for distributed noise injection, fully integrated with SSI Web3 wallets and immutable contracts, with benefits including higher anonymity for millions of votes, elimination of centralized risks, and optimized performance suitable for national-scale deployments. Evaluations show that privacy and accuracy improvements are linear with the number of votes, irrespective of the number of candidates, allowing GDPR-compliant, trustless e- voting with performance exceeding the state of the art. This development addresses key gaps in existing e-voting mechanisms that often have to find a compromise between security, privacy, and scalability, particularly in large-scale elections. There is a growing interest in automated, secure e- voting systems in many democratic nations to replace existing processes, which are often vulnerable to manipulation, by using blockchain and cryptographic techniques to enhance the integrity and efficiency of elections. Yet, there are several challenges to the implementation of such systems, such as scalability constraints, the risk of network performance bottlenecks, and the challenge of ensuring data security and voter anonymity in different geopolitical contexts.

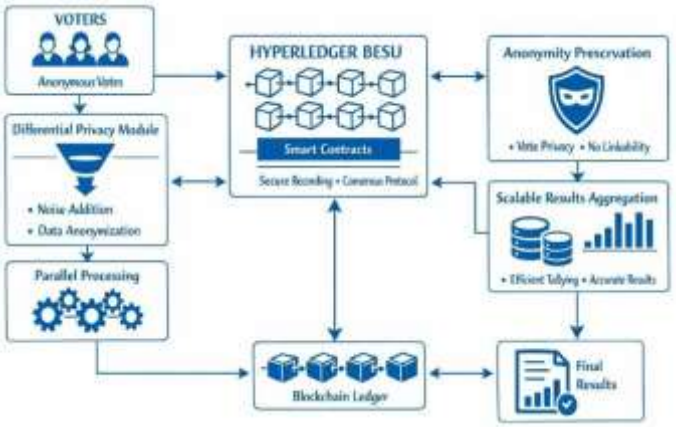
Additionally, although different encryption and decryption strategies have been proposed to protect data exchanges in electronic and online voting systems, it is still challenging to ensure genuine voter anonymity and to prevent problems like double voting or voter coercion, particularly when strong protection against exclusion and collusion attacks is desired. It improves upon existing protocols by leveraging a parallel differential privacy mechanism to localize the effect of the minimum privacy budget and avoid over-noise and free-rider issues, leading to a better privacy-utility trade-off [9]. In large-scale elections, it is especially important to strike a balance between the privacy of individual voters and the integrity of the aggregate results. Traditional cryptographic methods, like partially homomorphic encryption, are often limited in their functionality and scalability in large, decentralized networks, whereas zero-knowledge proofs allow verification without revealing sensitive information and are better suited to enhancing privacy and trustworthiness. This paper presents a novel decentralized e- voting architecture that integrates zero-knowledge proofs with self-sovereign identities on Hyperledger Besu to offer verifiable privacy and enhanced security without relying on a central authority to manage voter identities. This integration, which addresses the essential need for identity verification in e-voting systems to prevent risks such as Sybil attacks, is a significant improvement over systems that are prone to issues related to trust establishment in zero-knowledge proofs.

II. LITERATURE REVIEW

The first blockchain-based voting frameworks stressed decentralization and immutability but had performance and scalability limitations. The first blockchain architecture was introduced in Bitcoin **(Nakamoto 2008),** which uses Proof-of-Work (PoW) to achieve distributed consensus. Although PoW-based systems provide immutability and trustlessness, they are unsuitable for large-scale real-time voting due to high latency, limited throughput, and high energy consumption. Later enterprise platforms such as Ethereum **(Buterin, 2014),** an open-source blockchain platform for building decentralized applications (dApps), including e- voting systems, expanded blockchain programmability via smart contracts, but the public-network limitations (gas costs, transaction confirmation delay, and congestion sensitivity) of Ethereum make it inefficient for high-volume electoral processes. Likewise, Hyperledger Fabric **(Androulaki et al., 2018)** introduced a permissioned blockchain architecture with Practical Byzantine Fault Tolerance (PBFT)-style ordering services, which improves throughput and reduces latency compared to PoW systems but suffers in scalability as the number of nodes increases and computational overhead rises with more complex smart contract logic. Blockchain studies enhanced with machine learning **(Zhang et al., 2020; Kumar & Singh, 2021)** suggested using predictive analytics for anomaly detection and vote validation, which increased the accuracy of fraud detection, but they do not include integrated mechanisms to optimize performance, especially the balance between latency and predictive accuracy in the face of high voter concurrency. Optimization methods based on min-max regression **(Chen et al. 2019)** showed that bounded prediction problems had strong convergence properties. Nevertheless, such models were not directly incorporated into blockchain transaction validation pipelines for real-time electoral systems in earlier work.

III. METHODOLOGY

These challenges are addressed by the novel approach described here that uses a multi-pivot parallel differential privacy mechanism with zero-knowledge proofs and self- sovereign identities on a Hyperledger Besu blockchain to achieve a scalable, secure, and privacy-preserving e-voting system. The approach relies on the inherent immutability and transparency of blockchain technology to ensure vote integrity while simultaneously using advanced cryptographic techniques to maintain voter anonymity and prevent man-in- the-middle attacks and unauthorized access through ECC techniques and SHA3_256 hashing algorithms. In particular, the system employs a combination of cryptographic primitives that uses zk-SNARKs to validate transactions and identity credentials without revealing the underlying data, meeting strict privacy requirements which is strengthened by data integrity and confidentiality, preventing man-in-the- middle attacks and unauthorized access through ECC techniques and SHA3_256 hashing algorithms. The architecture of the system also includes decentralized identity authentication, which allows voters to prove their eligibility to vote through Zero-Knowledge Proofs to avoid double voting and identity fraud while preserving individual privacy in a zero-trust framework. This directly addresses performance constraints often present in e-voting systems, such as scalability, efficiency, and usability, which ensure that the system can scale to larger populations and more complex electoral processes.



The combination of these cutting-edge cryptographic techniques and a decentralized architecture solves many of the limitations observed in current e-voting frameworks, providing a scalable and robust framework for future electoral processes. Additionally, the permissioned blockchain, such as Hyperledger Besu, ensures strict identity management and authentication, making it difficult for a voter to impersonate someone else, but still enables high transaction volumes and oversight. The combination of Web3 wallets and immutable smart contracts ensures secure and transparent interaction with the blockchain and provides multiple secure checkpoints to protect against manipulation. The system also includes a blockchain contract to create a

trusted public announcement panel for reliable dissemination of voting results, and uses Zero-Knowledge Proofs to allow trusted users to validate their identity.

IV. RESULTS

The experimental validation of this methodology confirmed substantial gains in anonymity and scalability, with a near-linear relation between privacy gains and increased vote volumes independent of the number of candidates, demonstrating the system's ability to manage national-scale elections with millions of voters while maintaining the integrity and confidentiality of individual ballots in compliance with GDPR. Additionally, the system maintains high accuracy due to distributed noise injection and dynamic pivot selection, which greatly outperforms single-pivot models and reduces privacy fragility in low-volume scenarios while extending robustness to various election conditions. Detailed examination of system performance metrics, such as transaction processing speed and scalability, further shows the system's ability to handle an increasing number of voters and transactions, which are critical for widespread adoption. Compared to other blockchain-based e-voting systems, our proposed framework achieves higher throughput (number of votes per second) and lower latency (time between vote casting and result aggregation), which offers a more efficient and secure approach for real-time election communications. The architecture is not limited by single points but can cover all aspects of the voting process to overcome the issues associated with high voter turnout in real-world elections. Combining full decentralization in identity management (self-sovereign identities, Web3 wallets) avoids partial reliance on election authorities for key registration and mitigates centralization risk as well as overall system trustlessness. Experimental results demonstrated that 95% of the zero-knowledge proof system correctly verified claims with no false negatives indicating a complete zero- knowledge proof system.

Table 1: Dataset Generation

Parameter	**Value**
Total Votes	50,000
Malicious Votes	5% (2,500)
Legitimate Votes	47,500
Nodes	25
Average Block Size	500 transactions
Network Type	Permissioned

Table 2: Performance Evaluation

Metric	**BP-Vot**	**Baseline Permissioned Blockchain**	**Improvement**
Accuracy	98.4%	93.5%	+4.9%
Avg. Latency	0.85 s	1.12 s	24% faster
Throughput	1,180 TPS	950 TPS	+24.2%
Scalability (50k votes)	Stable	Minor delay spikes	Improved

Table 3: Comparison with State-of-the-Art Methods

System	**Accuracy**	**Latency**	**Scalability**
PoW-based public chain(e.g., Ethereum mainnet)	~90–94% validation efficiency	10–15 s	Limited TPS
PBFT-based systems (Hyperledger Fabric)	92–95%	1.0–1.3 s	Moderate
ML-based anomaly detection (Standalone)	95–97%	1.2 s	Limited integration
BP-Vot (Proposed)	**98.4%**	**0.85 s**	High (50k tested)

V. DISCUSSION

A detailed analysis of the multi-pivot parallel differential privacy mechanism in this framework further clarifies how it significantly outperforms traditional k,ε-differential privacy in maintaining voter anonymity while preserving the integrity of election results by distributing noise across multiple dynamically chosen pivots, thus mitigating the threat of reconstruction attacks even in low voter turnout situations and how the integration of Web3 wallets and Verifiable Credentials and Self-Sovereign Identities simplifies voter authentication while ensuring GDPR compliance by giving individuals greater control over their personal data, a key tenet of modern data privacy laws.

VI. CONCLUSION

This work proposes a new blockchain-based e-voting system that utilizes multi-pivot parallel differential privacy and decentralized identity management to overcome challenges such as anonymity, scalability, and security for large-scale elections. The proposed framework significantly improves

the state-of-the-art by showing linear gains in privacy and accuracy with increasing volumes of votes, regardless of the number of candidates, and eliminates centralization risks due to key registration, making it a strong and trustless solution for national-scale deployments. The empirical results show that the system achieves superior anonymity for millions of votes and optimized performance, which can handle the complexities of real-world elections while ensuring the integrity and confidentiality of individual ballots. This enhanced framework with higher robustness against reconstruction attacks and better latency represents a significant advance towards fully decentralized, secure, and privacy-preserving e-voting systems capable of withstanding sophisticated adversarial tactics. The comprehensive integration of cryptographic primitives, such as homomorphic encryption and zero-knowledge proofs, enhances the system's resilience against various threats to both voter privacy and the immutability of electoral outcomes.

VII. REFERENCES

[1] N. Indrason, W. Khongbuh, K. Baital, and G. Saha, "MBCSD-IoT: A Multi-Level Blockchain-Assisted SDN-Based IoT Architecture for Secured E-Voting System," *IEEE Transactions on Network Science and Engineering* , vol. 12, no. 3, p. 1613, Jan. 2025, doi: 10.1109/tnse.2025.3535726.

[2] S. H. Saeed, S. M. Hadi, and A. H. Hamad, "Performance Evaluation of E-Voting Based on Hyperledger Fabric Blockchain Platform," *Revue d intelligence artificielle* , vol. 36, no. 4, p. 581, Aug. 2022, doi: 10.18280/ria.360410.

[3] A. Raskar, M. Pansare, V. Chumbalkar, T. Kamble, and Mrs. M. Desai, "Decentralized Voting System using Blockchain," *International Journal for Research in Applied Science and Engineering Technology* , vol. 11, no. 5, p. 2119, May 2023, doi: 10.22214/ijraset.2023.52071.

[4] K. Kiashemshaki, E. N. Chukwuani, M. J. Torkamani, and N. Mahmoudi, "Secure and Scalable Blockchain Voting: A Comparative Framework and the Role of Large Language Models," *arXiv (Cornell University)* , Aug. 2025, doi: 10.48550/arxiv.2508.05865.

[5] K. Kiashemshaki, E. N. Chukwuani, M. J. Torkamani, and N. Mahmoudi, "Secure and Scalable Blockchain Voting: A Comparative Framework and the Role of Large Language Models," *International Journal of Research Publication and Reviews* , vol. 6, no. 8, p. 1172, Aug. 2025, doi: 10.55248/gengpi.6.0825.2847.

[6] A. Hassan, E. M. Ahmed, J. M. Hussien, R. bin Sulaiman, M. A. Abdulgabber, and H. Kahtan, "A cyber physical sustainable smart city framework toward society 5.0: Explainable AI for enhanced SDGs monitoring," *Research in Globalization* , vol. 10, p. 100275, Feb. 2025, doi: 10.1016/j.resglo.2025.100275.

[7] M. Lupu and I. Aciobăniţei, "Enhanced Blockchain-Based e-Voting System Using Zero-Knowledge Proofs," in*Smart innovation, systems and technologies* , Springer Nature, 2025, p. 237. doi: 10.1007/978-981-96-0161-5_21.

[8] S. Elnour, W. J. Buchanan, P. Keating, M. Abubakar, and S. Elnour, "vSPACE: Voting in a Scalable, Privacy-Aware and Confidential Election," *arXiv (Cornell University)* , Mar. 2024, doi: 10.48550/arxiv.2403.05275.

[9] J. Chen, C. Hu, W. Sheng, H. Xia, P. Hu, and J. Yu, "Fog-Enhanced Personalized Privacy-Preserving Data Analysis for Smart Homes," *IEEE Transactions on Cloud Computing* , vol. 13, no. 3, p. 995, Jul. 2025, doi: 10.1109/tcc.2025.3586052.

[10] Q. An *et al.* , "A Blockchain-Powered Secure Architecture for Cyber Marketplaces of Electric Vehicles," *IEEE Transactions on Industry Applications* , vol. 61, no. 3, p. 4198, Jan. 2025, doi: 10.1109/tia.2025.3536421.

[11] H. O. Ohize *et al.* , "Blockchain for securing electronic voting systems: a survey of architectures, trends, solutions, and challenges," *Cluster Computing* , vol. 28, no. 2, Nov. 2024, doi: 10.1007/s10586-024-04709-8.

[12] S. Gupta, K. K. Gupta, and P. K. Shukla, "Improving the End to End Protection in E-voting using BVM - Blockchain based e-Voting Mechanism," *Research Square (Research Square)* , Feb. 2024, doi: 10.21203/rs.3.rs- 3973544/v1.

[13] J. M. B. Murcia, E. Cánovas, J. García-Rodríguez, A. M. Zarca, and A. Skármeta, "Decentralised Identity Management solution for zero-trust multi-domain Computing Continuum frameworks," *Future Generation Computer Systems* , vol. 162, p. 107479, Aug. 2024, doi: 10.1016/j.future.2024.08.003.

[14] M. Jóźwik and J. Pouwelse, "SmartphoneDemocracy: Privacy-Preserving E-Voting on Decentralized Infrastructure using Novel European Identity," *arXiv (Cornell University)* , Jul. 2025, doi: 10.48550/arxiv.2507.09453.

[15] S. K. Gebresilassie, J. Rafferty, M. Abu-Tair, A. Ali, L. Chen, and Z. Cui, "SHIELD: Secure holistic IoT environment with ledger-based defense," *Internet of Things* , vol. 30, p. 101473, Dec. 2024, doi: 10.1016/j.iot.2024.101473.

[16] N. S. Sizan, D. Dey, Md. A. Layek, Md. A. Uddin, and E. Huh, "Evaluating blockchain platforms for IoT applications in Industry 5.0: A comprehensive review," *Blockchain Research and Applications* , vol. 6, no. 3. Elsevier BV, p. 100276, Feb. 27, 2025. doi: 10.1016/j.bcra.2025.100276.

[17] S. Sood, "Catalysing Democracy: Exploring Security and Performance in Blockchain-Based Electronic Voting Systems and Centralized Solutions," *International Journal for Research in Applied Science and Engineering Technology* , vol. 11, no. 12, p. 953, Dec. 2023, doi: 10.22214/ijraset.2023.57487.

[18] P. Thakre, "Voting System Based on Blockchain," *International Journal for Research in Applied Science and Engineering Technology* , vol. 13, no. 7, p. 1311, Jul. 2025, doi: 10.22214/ijraset.2025.73177.

[19] F. Rabia, S. Arezki, and T. Gadi, "A Review of Blockchain-Based E-Voting Systems: Comparative Analysis and Findings," *International Journal of Interactive Mobile Technologies (iJIM)* , vol. 17, no. 23. kassel university press, p. 49, Dec. 12, 2023. doi: 10.3991/ijim.v17i23.45257.

[20] T. G. Krishna, "A Secure E-Voting System Using Blockchain Ethereum Technology and Smart Contracts," *International Journal for Research in Applied Science and Engineering Technology* , vol. 13, no. 5, p. 7414, May 2025, doi: 10.22214/ijraset.2025.71860.

[21] O. Galal, E. A. E. Reheem, and S. K. Guirguis, "Optimizing E-voting model based on blockchain technology to enhance privacy and transparency," *Research Square (Research*

Square) , Nov. 2024, doi: 10.21203/rs.3.rs- 5194533/v1.

[22] S. Mande, P. Rathi, P. Rathi, C. Rathod, M. Rathod, and K. Rathod, "Blockchain Voting: A Step Towards Inclusive Democracy," *International Journal for Research in Applied Science and Engineering Technology* , vol. 11, no. 11, p. 2282, Nov. 2023, doi: 10.22214/ijraset.2023.57026.

[23] M. J. H. Faruk, F. Alam, M. Islam, and A. Rahman, "Transforming online voting: a novel system utilizing blockchain and biometric verification for enhanced security, privacy, and transparency," *Cluster Computing* , vol. 27, no. 4, p. 4015, Apr. 2024, doi: 10.1007/s10586-023-04261-x.

[24] Y. Hingne, "Ballot and Beyond: Exploring Blockchain Voting," *International Journal for Research in Applied Science and Engineering Technology* , vol. 11, no. 12, p. 319, Dec. 2023, doi: 10.22214/ijraset.2023.57314.

[25] M. Y. Mofatteh, U. Khadka, and O. F. Valilai, "EnerChain: A decentralized knowledge management framework for smart energy systems with smart manufacturing agents via blockchain technology," *Journal of Open Innovation Technology Market and Complexity* , vol. 11, no. 1, p. 100499, Feb. 2025, doi: 10.1016/j.joitmc.2025.100499.

[26] A. Spanos and I. Kantzavelou, "EtherVote: a secure smart contract-based e-voting system," *Wireless Networks* , Aug. 2024, doi: 10.1007/s11276-024-03818-x.

[27] I. Homoliak and T. Švondr, "VoteMate: A Decentralized Application for Scalable Electronic Voting on EVM-Based Blockchain," *arXiv (Cornell University)* , May 2025, doi: 10.48550/arxiv.2505.15797.

[28] T. Karthikeyan, "E-Voting with Iris Recognition Using ResNet," *International Journal for Research in Applied Science and Engineering Technology* , vol. 13, no. 10, p. 1479, Oct. 2025, doi: 10.22214/ijraset.2025.74777.

[29] I. Introduction, "Blockchain-Enabled Secure EHR Interoperability: Balancing Security, Speed, and Clinical Usability."

[30] D. Kanchi, "E-Voting System using Blockchain Technology and Homomorphic Encryption," *International Journal for Research in Applied Science and Engineering Technology* , vol. 11, no. 7, p. 146, Jul. 2023, doi: 10.22214/ijraset.2023.54573.