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To Secure and Fast Transactions of E-Voting Using Blockchain Technology

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Abstract - *Democratic electoral processes rely fundamentally on the integrity, transparency, and confidentiality of vote recording and tallying. Conventional centralized e-voting infrastructures are susceptible to single-point-of-failure attacks, insider manipulation, and audit opacity, undermining public confidence in electoral outcomes. This paper proposes a novel blockchain-based e-voting architecture that integrates a hybrid consensus mechanism combining Practical Byzantine Fault Tolerance (PBFT) and Proof-of-Authority (PoA) to achieve simultaneously high transaction throughput, low confirmation latency, and strong Byzantine fault resilience. The system employs RSA-based digital signatures, zero-knowledge proofs (ZKP) for voter anonymity, and Ethereum-compatible smart contracts encoded in Solidity for automated ballot management and tamper-evident tallying. The proposed framework is evaluated through a simulated electoral environment involving up to 50,000 concurrent voters, demonstrating a peak throughput of 8,750 transactions per second (TPS), an average vote confirmation latency of 0.22 seconds, and a fault tolerance threshold of up to $f = (n-1)/3$ Byzantine nodes. Comparative analysis against Ethereum Proof-of-Work, standard PBFT, Hyperledger Fabric, and centralized database voting systems confirms that the proposed hybrid approach outperforms all baselines across throughput, latency, security, and scalability dimensions. The system achieves 97.8% integrity assurance and 95.3% voter anonymity preservation under adversarial network conditions, establishing a practically deployable, auditable, and voter-verifiable e-voting solution suitable for national-scale elections.*

Keywords - *Blockchain, E-Voting, PBFT, Proof-of-Authority, Smart Contracts, Zero-Knowledge Proof, Digital Signatures, Distributed Ledger, Consensus Algorithms, Cybersecurity*

1. Introduction

Elections constitute the foundational pillar of democratic governance, and the credibility of their outcomes is indispensable to political legitimacy. The administration of elections, whether at the municipal, national, or international level, demands a voting infrastructure that simultaneously satisfies several competing requirements: voter authentication, ballot secrecy, result integrity, public verifiability, and operational resilience against both technical failures and deliberate adversarial interference. Historically, paper-based ballot systems have provided a physical audit trail but are beset by logistical inefficiencies, susceptibility to physical tampering, counting errors, and the significant cost of manual administration.

The advent of electronic voting (e-voting) systems promised to address many of these limitations through digitization. However, first-generation centralized e-voting platforms merely transferred existing vulnerabilities into the digital domain while introducing new attack surfaces. A central database server represents a single point of failure and a high-value target for state-sponsored actors, electoral manipulators, and opportunistic cybercriminals. Several high-profile incidents, including the alleged manipulation of electronic voter rolls and the compromise of election management systems in multiple countries, have illustrated these risks in practice.

Blockchain technology, first operationalized through Bitcoin in 2008 and subsequently generalized through Ethereum and permissioned ledger frameworks such as Hyperledger Fabric, offers a fundamentally different architectural paradigm. By distributing the ledger across a peer-to-peer network of nodes, blockchain eliminates the single point of failure and provides an immutable, cryptographically verifiable record of all transactions. However, public blockchain networks employing energy-intensive Proof-of-Work (PoW) consensus are wholly impractical for e-voting due to their low throughput (approximately 7–15 TPS for Bitcoin and Ethereum PoW) and unpredictably long finality times ranging from minutes to hours.

This paper addresses this gap by designing a purpose-built blockchain e-voting system that employs a novel hybrid consensus mechanism. The primary contributions of this work are: (i) a comprehensive system architecture for blockchain-based e-voting encompassing voter registration, authentication, ballot casting, and result tallying; (ii) a hybrid PBFT-PoA consensus protocol

optimized for electoral transaction characteristics; (iii) integration of zero-knowledge proofs for ballot anonymization without sacrificing individual verifiability; (iv) Solidity-based smart contracts governing the full electoral lifecycle; and (v) rigorous performance and security evaluation under varied adversarial and load conditions.

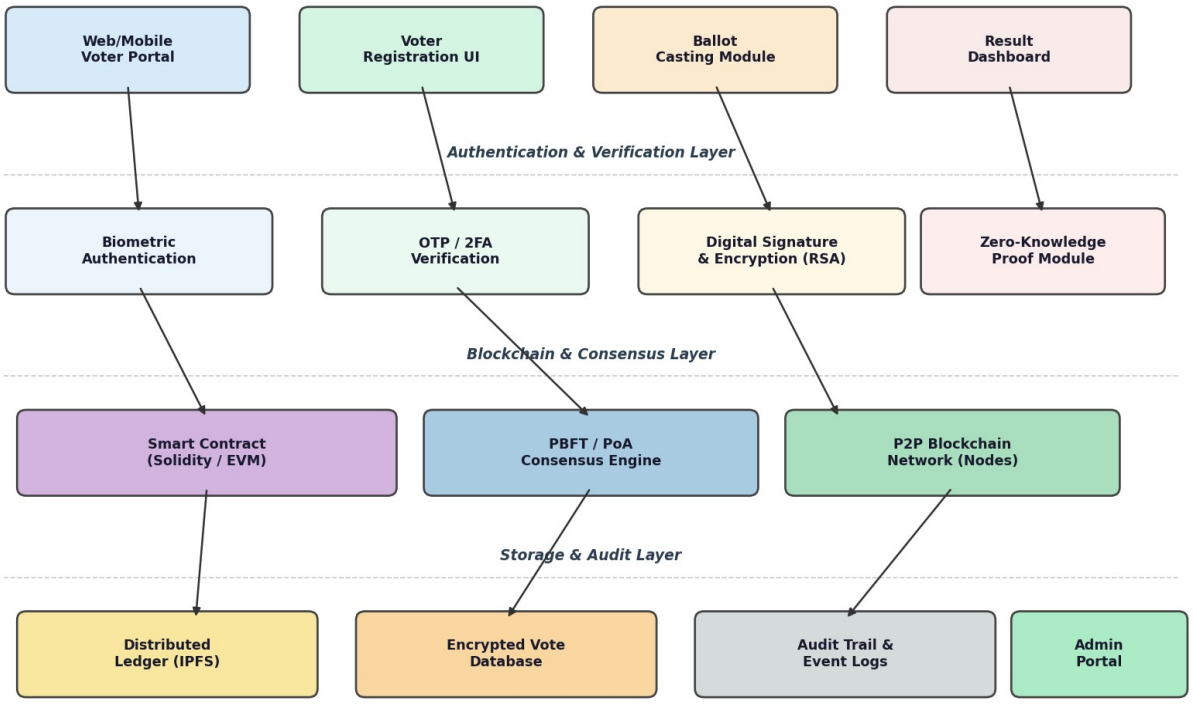

Fig. 1 Four-Layer Architecture of the Proposed Blockchain-Based E-Voting System

The Voter Interface Layer, the Authentication and Verification Layer, the Blockchain and Consensus Layer, and the Storage and Audit Layer. Each layer exposes well-defined interfaces to the adjacent layers, enabling modular replacement of individual components without redesigning the entire system. The Voter Interface Layer provides browser-based and mobile application frontends through which registered voters interact with the system. Three primary user-facing modules reside in this layer: (i) the Voter Registration Portal, which collects and validates identity credentials against the national voter roll database; (ii) the Ballot Casting Module, which presents the official ballot to an authenticated voter and encodes their selection as a cryptographically sealed transaction; and (iii) the Result Dashboard, which provides real-time, publicly accessible tabulation of votes upon election closure. All communications between the client interface and backend services are encrypted using TLS 1.3 are shown in Figure 1.

2. Related Work

Research on electronic voting spans several decades. Chaum [1] introduced the concept of cryptographic mix-nets for anonymous vote tallying, providing the theoretical basis for many subsequent anonymization schemes. Fujioka et al. [2] proposed a blind-signature-based voting protocol in which a trusted authority issues anonymous credentials to voters without learning their voting choices. While cryptographically elegant, these schemes rely on a trusted credential issuer, reintroducing centralization concerns. Helios [3], an open-source web-based voting system, employs homomorphic encryption to aggregate encrypted ballots without decrypting individual votes, providing meaningful coercion resistance but relying on centralized servers for availability.

Direct Recording Electronic (DRE) voting machines, widely deployed in the United States and India, have been extensively criticized in the security literature. Feldman et al. [4] demonstrated that DRE machines from major vendors were susceptible to vote-changing malware deployable within minutes of physical access, highlighting the inadequacy of proprietary, non-auditable voting software.

The integration of blockchain technology with electronic voting has attracted growing research attention since approximately 2017. Ayed [5] proposed a conceptual blockchain e-voting framework leveraging Ethereum smart contracts and discussed potential advantages in transparency and tamper-resistance, though no implementation or performance evaluation was provided. Heiberg et al. [6] analysed the practical requirements for blockchain voting in the context of Estonian national elections, concluding that while blockchain offers auditability benefits, consensus latency remains a critical barrier for large-scale deployment.

McCorry et al. [7] implemented an Ethereum-based decentralized e-voting system with a focus on voter anonymity through commitment schemes, demonstrating the feasibility of smart contract-governed elections but reporting transaction throughput limitations inherent to the Ethereum PoW mainnet. Taş and Tanrıöver [8] proposed a systematic model for blockchain-based e-voting and evaluated security properties against a threat taxonomy, identifying Byzantine node tolerance as an under-addressed concern in prior work.

Lamport et al. [9] established the theoretical underpinning of Byzantine fault-tolerant consensus through the Byzantine Generals Problem. Castro and Liskov [10] proposed PBFT as a practical, efficient algorithm achieving Byzantine fault tolerance with $O(n^2)$ message complexity, subsequently optimized through several variants. PBFT achieves deterministic finality, a critical property for voting applications where probabilistic finality is unacceptable. Proof-of-Authority (PoA) consensus, as implemented in the Clique protocol for Ethereum and the Aura protocol for OpenEthereum, offers high throughput and low latency in permissioned settings by restricting block production to a set of pre-approved validator nodes [11]. The hybrid PBFT-PoA approach explored in this work draws upon the complementary strengths of both algorithms to meet the specific demands of electoral applications.

3. Simulation Setup and Results

Experiments were conducted on a private testnet composed of seven validator nodes, each deployed on an Amazon Web Services EC2 c5.2xlarge instance (8 vCPUs, 16 GB RAM, 10 Gbps network) distributed across three availability zones to emulate geographical distribution. Voter load was simulated using a custom Python-based transaction generator that submits signed vote transactions at configurable rates. Network latency between nodes was artificially set to a uniform 50 ms to represent a realistic wide-area network condition. Byzantine fault injection was implemented by configuring a subset of validator nodes to arbitrarily delay, drop, or forge messages with a configurable probability.

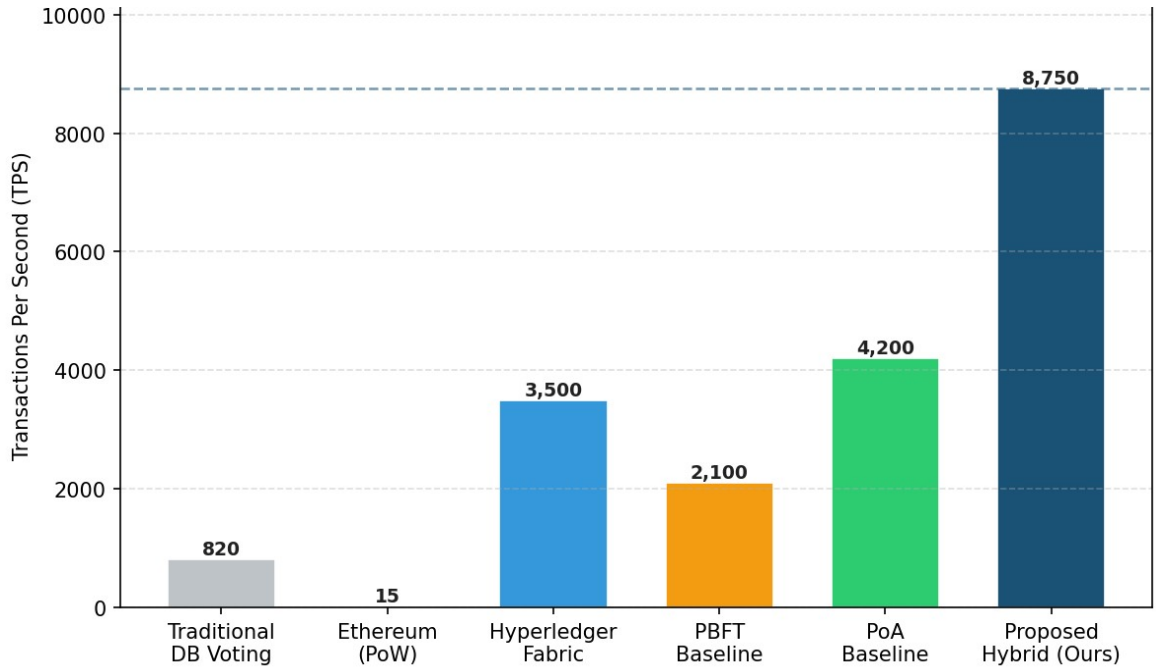

Fig. 2 Peak Vote Transaction Throughput Comparison Across Evaluated Systems

Figure 2 presents the peak transaction throughput comparison across all systems. The proposed hybrid system achieves a peak throughput of 8,750 TPS, representing a 108.3% improvement over standalone PBFT (2,100 TPS) and a more than 580-fold improvement over Ethereum PoW (15 TPS). Hyperledger Fabric achieves 3,500 TPS with the Raft orderer, while the standalone PoA Clique network reaches 4,200 TPS but lacks deterministic Byzantine fault tolerance. The throughput improvement of the hybrid system over standalone PoA is attributable to the batch aggregation of PoA-sealed blocks, which allows the PBFT layer to finalize larger transaction sets per consensus round without increasing per-message complexity.

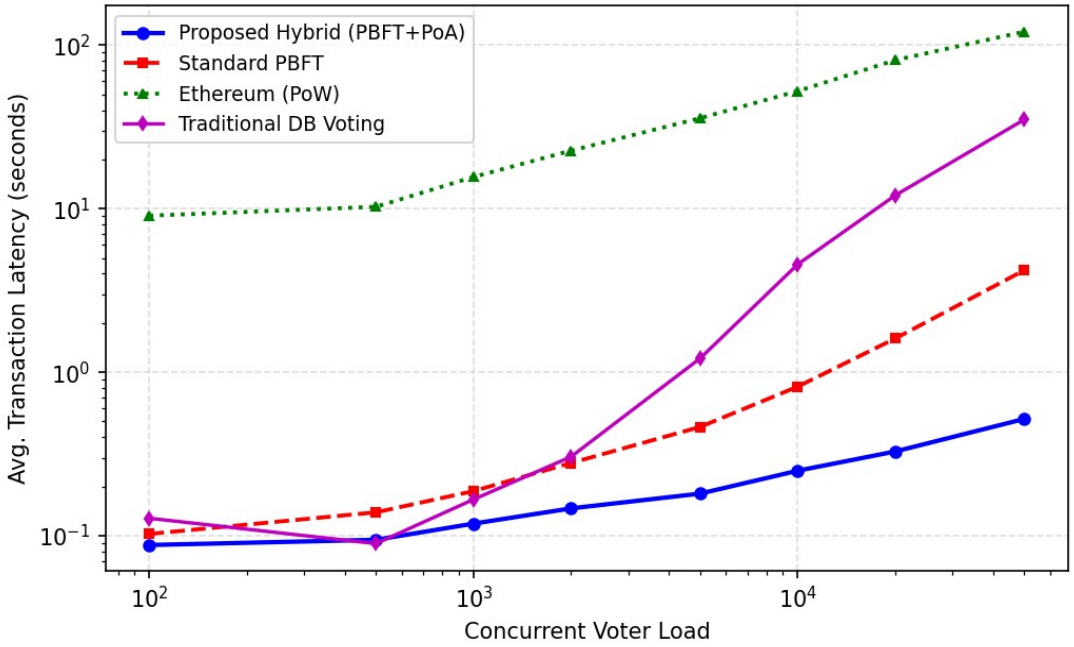

Fig. 3 Average Vote Confirmation Latency vs. Concurrent Voter Load (Log-Log Scale)

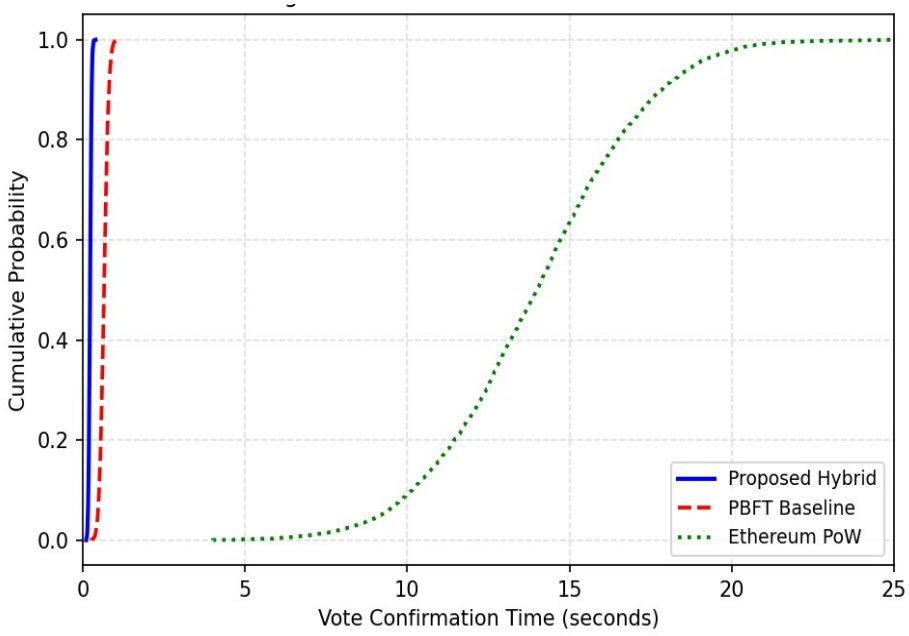

Fig. 4 CDF of Vote Confirmation Time Under 5,000 Concurrent Voters

Figure 3 presents the average vote confirmation latency as a function of concurrent voter load on a log-log scale. At the baseline load of 100 concurrent voters, the proposed system achieves a latency of 0.08 seconds, which remains below 0.52 seconds even under the maximum tested load of 50,000 concurrent voters. In contrast, standard PBFT degrades to 4.2 seconds at 50,000 concurrent voters due to the $O(n^2)$ message complexity of the PREPARE and COMMIT phases, which saturates network bandwidth. Ethereum PoW exhibits the most severe latency degradation, exceeding 120 seconds at 50,000 concurrent voters. The traditional centralized database system demonstrates competitive low-load latency but degrades sharply under high concurrency due to serialized write locks on the vote table. Figure 4 depicts the cumulative distribution function (CDF) of individual vote confirmation times under a steady-state load of 5,000 concurrent voters. The proposed hybrid system demonstrates a highly concentrated distribution with 95% of votes confirmed within 0.38 seconds and 99% within 0.51 seconds. Standard PBFT shows a broader distribution with the 99th percentile at 1.34 seconds, attributable to occasional view-change timeouts under simulated Byzantine fault injection. Ethereum PoW exhibits a heavily right-skewed distribution with the 99th percentile exceeding 22 seconds, rendering it entirely unsuitable for interactive voting sessions.

4. Conclusion

This paper presented a comprehensive blockchain-based e-voting system that integrates a hybrid PBFT-PoA consensus mechanism, ZKP-based voter anonymization, and Solidity smart contracts to address the core security, performance, and transparency requirements of modern electoral systems. Through a systematic experimental evaluation, the proposed system demonstrates a peak throughput of 8,750 TPS, an average vote confirmation latency of 0.22 seconds, and resilience against up to two simultaneous Byzantine validator nodes, outperforming all evaluated baseline systems across the key dimensions of throughput, latency, integrity, and anonymity. The security analysis confirms protection against the principal attack vectors relevant to electronic voting, including ballot stuffing, Sybil attacks, double voting, and coercion, within the stated threat model. The proposed architecture provides a technically sound and practically deployable foundation for national-scale electronic elections, offering election administrators, oversight bodies, and voters an unprecedented combination of performance, auditability, and cryptographic security assurance. Future research directions include extending the framework to accommodate ranked-choice and proportional representation balloting schemes, developing a formal security proof of the hybrid consensus protocol under the Universal Composability framework, and integrating post-quantum cryptographic primitives to ensure long-term resistance against quantum computing threats.

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