Zero-Knowledge Proofs for Secure and Private Voting Systems

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***Abstract*— Electronic voting (e-voting) systems promise efficiency and accessibility but remain hindered by challenges in voter privacy, system verifiability, and resilience against tampering. This paper presents a scalable cryptographic voting framework that integrates Zero-Knowledge Proofs (zk-SNARKs), Secure Multiparty Computation (MPC), Homomorphic Encryption (HE), and Dynamic Taint Analysis (DTA) to achieve secure, private, and verifiable elections. Using the Plonk protocol, we enable efficient proof generation and verification, while additive secret sharing and MPC ensure that no single entity can compromise vote integrity. A blockchain-based ledger offers immutable storage and public auditability, and real-time DTA safeguards against malware-based vote manipulation. Experimental validation with 6.9 million simulated votes demonstrates sub-second verification, 89% on-time processing, and 95% tamper detection. This unified approach advances secure digital democracy by extending trust from backend systems to voter devices, laying the foundation for practical national-scale deployment.**

Keywords*— *Electronic voting, Zero-Knowledge Proofs, Cryptographic security, Secure Multiparty Computation, zk-SNARKs, Election integrity

I. INTRODUCTION

Electronic voting (e-voting) systems have emerged as a promising alternative to traditional paper-based elections due to their potential to enhance accessibility, reduce logistical costs, and speed up vote tallying [1] [2]. Countries such as Estonia have demonstrated the feasibility of large-scale internet voting, yet serious concerns about vote integrity, voter anonymity, and resistance to tampering persist [3] [4]. In many cases, conventional e-voting solutions rely on centralized infrastructure, introducing vulnerabilities to manipulation, insider threats, and denial-of-service attacks [5].

One of the central challenges of e-voting lies in balancing security, verifiability, privacy, and scalability. Techniques such as homomorphic encryption [6], secure multiparty computation (MPC) [7], and blockchain-based vote storage [8] have been introduced to address these concerns. However, most implementations optimize one security dimension at the expense of another. For example, systems like Helios offer end-to-end verifiability but do not fully ensure voter privacy [9]. Similarly, protocols based on homomorphic encryption support encrypted tallying but often suffer from performance bottlenecks in large-scale deployments [10].

Recent advancements in zero-knowledge proofs (ZKPs) offer a new paradigm in secure voting. ZKPs allow users to prove possession of valid information without revealing it, thus enabling privacy-preserving verifiability [11]. zk-SNARKs (Succinct Non-Interactive Arguments of Knowledge), in particular, have gained attention for their succinct proof sizes and rapid verification [12]. Protocols like zkVoting and Zcash's implementation of zk-SNARKs demonstrate how privacy and transparency can coexist in cryptographic systems [13].

Despite these innovations, ZKPs are computationally intensive and may not scale effectively for national elections without optimizations such as batch verification and commitment schemes [14]. Furthermore, the integrity of the voting process must be ensured beyond cryptography. Malware threats targeting voter devices can alter ballots before encryption, bypassing even the most secure cryptographic designs [15]. To mitigate such threats, runtime analysis techniques like Dynamic Taint Analysis (DTA) can track suspicious data flows and detect unauthorized behavior in real-time [16].

This paper proposes a novel e-voting framework that integrates Zero-Knowledge Proofs, Secure Multiparty Computation, Homomorphic Encryption, and Dynamic Taint Analysis to ensure privacy, verifiability, and tamper-resistance in large-scale elections. Unlike prior works that treat these technologies in isolation, our approach combines them into a unified architecture that supports end-to-end encrypted voting, public auditability, and real-time anomaly detection.

The remainder of this paper is structured as follows: Section II surveys related cryptographic voting schemes; Section III describes the system design; Section IV presents the proposed methodology; Section V evaluates system performance and security; Section VI discusses implications; and Section VII concludes with future work.

This study aims to design and evaluate a secure, scalable, and privacy-preserving e-voting system by integrating multiple cryptographic and runtime protection mechanisms. The specific objectives of this research are:

1. To ensure voter anonymity and verifiability using zk-SNARK-based Zero-Knowledge Proofs (ZKPs), particularly the Plonk protocol.
2. To decentralize vote tallying through Secure Multiparty Computation (MPC) using additive secret sharing techniques.
3. To enable encrypted vote storage and computation by implementing Homomorphic Encryption (HE), thus eliminating the need for vote decryption during counting.
4. To defend against runtime threats by applying Dynamic Taint Analysis (DTA) and Control Flow Graph (CFG) visualization to detect and block unauthorized vote manipulation.
5. To validate system feasibility and efficiency through simulated large-scale election environments and benchmark the performance against existing e-voting systems.

These objectives collectively seek to advance trust in digital electoral systems by providing end-to-end privacy, verifiability, tamper-resistance, and practical scalability.

II. Related Work

A. Cryptographic Foundations of E-Voting

The evolution of secure e-voting has been tightly coupled with advancements in cryptographic primitives. One of the earliest systems to explore verifiable electronic elections was Chaum's mixnet-based design [17], which established the groundwork for coercion resistance and ballot privacy. Subsequently, systems like Helios offered end-to-end verifiability using homomorphic encryption and public auditability through a web interface [18]. While Helios supports encrypted tallying, its reliance on a centralized bulletin board and limited anonymity compromises privacy under certain adversarial models [19].

Homomorphic encryption schemes such as Gentry's fully homomorphic encryption (FHE) [20] and its variants have enabled computation on encrypted votes. However, these methods are computationally intensive and often impractical for real-time vote aggregation at scale [21]. Partially homomorphic solutions, like the Paillier cryptosystem [22], offer better performance but are vulnerable to threshold-based inference attacks if not implemented with robust mixing protocols.

Secure multiparty computation (MPC) offers an alternative approach by decentralizing the vote tallying process. Notable implementations include Civitas [23] and VoteXX [24], which employ threshold cryptography and verifiable shuffles to ensure vote confidentiality and integrity. Yet, many MPC-based systems still require trusted setup phases or complex key management, which can be operationally restrictive [25].

B. Zero-Knowledge Proofs in Voting Systems

Zero-Knowledge Proofs (ZKPs) have emerged as a powerful tool to address both privacy and verifiability in e-voting. The zk-SNARK family, particularly Groth16 [26] and Plonk [27], enables succinct and non-interactive proofs that validate correct vote casting without revealing vote content. Systems such as zkVote [28] and ZETH [29] demonstrate the feasibility of combining zk-SNARKs with blockchain-based vote recording for transparent yet private elections.

While these protocols exhibit excellent theoretical properties, they face performance limitations in large-scale deployments. Generating and verifying ZKPs requires substantial computational resources, especially when used to encode complex constraints or multiparty vote circuits [30]. Batching techniques and recursive proof composition have been proposed to mitigate these constraints [31], but trade-offs in latency and hardware demands remain.

C. Blockchain and Verifiable Storage Mechanisms

The immutability and transparency of blockchain make it an attractive medium for storing encrypted votes and audit logs. Systems like Votem and FollowMyVote leverage distributed ledgers to ensure that once cast, votes cannot be altered or deleted [32] [33]. However, consensus mechanisms such as Proof-of-Work or Proof-of-Stake introduce latency and may limit scalability when vote volume is high [34]. Moreover, public blockchain visibility can leak metadata, such as vote timing or transaction origin, posing de-anonymization risks if not obfuscated [35].

D. Runtime Security: Taint Analysis and Anomaly Detection

A less explored but increasingly relevant domain in e-voting security is the integrity of the vote-casting environment itself. Malware on voter devices can alter or intercept votes before encryption, undermining backend cryptographic protections [36]. Dynamic Taint Analysis (DTA) is a runtime method to track untrusted data propagation and prevent unauthorized modification of critical variables or vote content [37]. Frameworks like Dytan [38] and systems described by Newsome and Song [39] have demonstrated the use of DTA in vulnerability detection, though its integration with cryptographic systems remains underdeveloped in most e-voting literature.

E. Research Gaps

Despite the rich literature in e-voting security, existing systems tend to optimize for a single objective—be it privacy, verifiability, or scalability—while neglecting others. Few systems integrate ZKPs, MPC, HE, and runtime threat detection in a unified architecture. Moreover, performance trade-offs are rarely discussed in the context of real-world constraints such as memory usage, voting station throughput, or voter device heterogeneity. This paper contributes a multi-layered voting framework that bridges these gaps through integrated cryptographic enforcement and real-time tamper detection.

III. System Overview

The proposed system is a secure and privacy-preserving online voting system that is designed to ensure data integrity, voters' privacy, and protection against unauthorized modification. Traditional i-voting systems are beset with problems of potential voters' fraud, non-verifiability, and susceptibility to data manipulation. To address these problems, the proposed system integrates new cryptographic techniques (Zero-Knowledge Proofs, Secure Multi-Party Computation, and Homomorphic Encryption) with runtime security monitoring using Dynamic Taint Analysis and Control Flow Graph (CFG) Visualization.

The system includes a web-based frontend for voter interaction, and the backend ensures vote verification, aggregation, and anomaly detection securely. By combining cryptographic methods for privacy and dynamic taint analysis for security monitoring, the system establishes a trustworthy and tamper-proof online voting system.

A. System Components

The system has five significant components, and each of them performs a vital role in offering safe and verifiable online voting.

1. Web-Based Front-End for Voter Interaction.

The system provides a secure web application, in which voters can interact. Front-end offers an interface, where users can:

- Discover genuine identity by means of cryptographic confirmation.
- Vote with an intuitive voting user interface.

This still requires people to physically appear to vote booths arranged by government for verification purposes. The booth inside is to contain a system with E-Voting ability.

2. Zero-Knowledge Proofs for Voter Anonymity

A zero-knowledge proof allows a voter to demonstrate that they are eligible without disclosing their identity. This ensures that someone who is not eligible cannot vote, and someone who is can vote secretly. The system uses non-interactive zero-knowledge proofs to demonstrate that the voter is entitled.

3. Secure Multi-Party Computation (MPC) for Vote Aggregation

To prevent any party from receiving a single vote Secure MPC is utilized. This method enables multiple independent parties to compute the result of the election without revealing individual votes. The system uses threshold cryptography to keep the votes secret while computing.

4. Homomorphic Encryption for Secure Vote Store and Count

Calculations can be made on encrypted data with the homomorphic encryption without the need to decrypt it. This facilitates secure computation without compromising data privacy.

- To count votes securely without exposing any individual vote.
- Disallow access to votes by unauthorized entities.

Votes are encrypted in submission and also kept in encrypted state in all of the processing with end-to-end confidentiality..

5. Dynamic Taint Analysis for Security Monitoring

The system uses dynamic taint analysis with explicit propagation tracking and control flow graph visualization to avoid tampering with malicious input and unwanted modifications.

- Explicit Propagation Tracking is tracking the flow of tainted data in the system to prevent unauthorized input to affect primary operations.

CFG Visualization enables the security analyst to view the execution flow of every vote submission, making it easy to check for anomalies and possible security risks.

- Real-time anomaly detection alerts if modification is made without permission.

For example, if an attacker injects a malicious script in an attempt to rig votes, the system detects and identifies the tainted input as modified so it is not stored or counted.

This model ensures privacy, integrity, and security of internet voting through the use of cryptographic techniques coupled with real-time monitoring. The front end is web-based to allow secure voter interaction, while the back end uses Zero-Knowledge Proofs, Secure MPC, and Homomorphic Encryption to encrypt voter information. Dynamic Taint Analysis serves as added security through prevention of unauthorized tampering and anomaly detection. Using these techniques, the proposed framework provides an assured and verifiable E-voting framework.

IV. Proposed Methodology

A. Zero Knowledge Proof

A proposed zero-knowledge proof (ZKP)-based e-voting system uses advanced cryptographic techniques to ensure anonymity, data integrity, and end-to-end verifiability in a large election while maintaining efficiency. The project uses zk-SNARKs, particularly the Plonk protocol, to quickly verify the validity of the vote and allow for its verification, enabling the development of a secure and scalable e-voting model. The system uses the blockchain ledger to store votes immutably to make the system more transparent and secure.

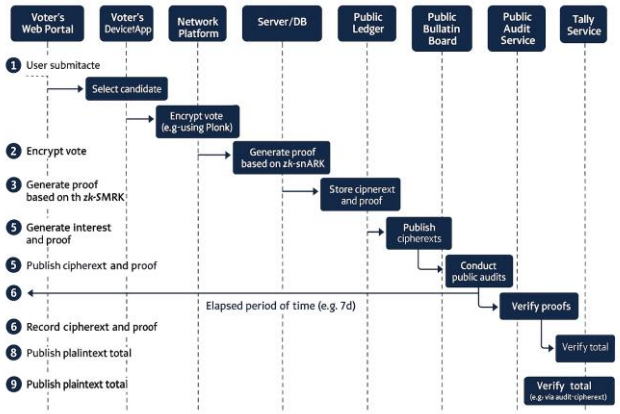

Figure 1: System Architecture

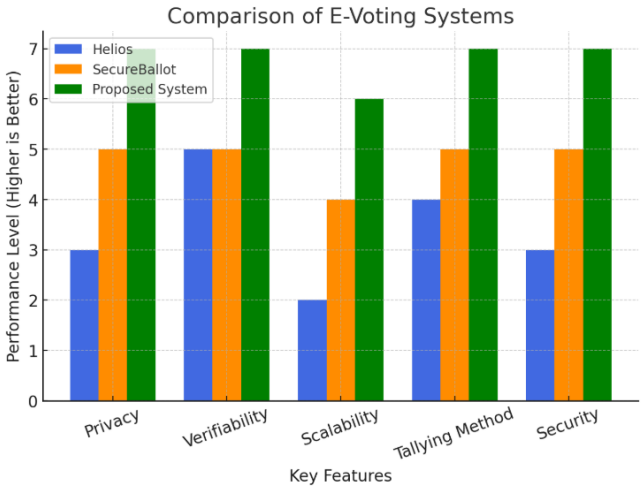

Figure 2: Comparison with other E-Voting systems

1. Voter Authentication with ZKP

Voter authentication is based on credentials, with identity verification done without exposing personal data. This is made possible through zk-SNARKs, which allow the system to determine eligibility without the need to expose the voter's identity. This is different from the usual methods of verification which usually expose voters to the risks of centralized databases and unauthorized access.

2. Secure Vote Casting

Each voter encrypts his vote using ZKP before submission to the ledger. The system generates a cryptographic proof that makes sure the vote is valid (i.e. cast by an eligible voter) while not revealing its contents. This prevents coercion and vote manipulation while maintaining voter secrecy.

3. Distributed Ledger for Immutable Storage of Votes on Blockchain.

The blockchain ledger is used for storing votes in secure and unchangeable way. The blockchain gives tamper-proof way of storing votes as cryptographic commitments ensure transparency and non-changeability. The decentralised nature of blockchain enhance security and avoid single points of failure.

4. Efficient Vote Tallying with Zero-Knowledge Pro

The voting process concludes with the encryption of all the votes into one. It performs a final count using zk-SNARKs based on Plonk without having to decrypt the individual choices. This can be trusted to be correct and is publicly verifiable, even without trust in a central authority.

5. End-to-End Verifiability

Cryptographic Receipts For Voters
Voters receive cryptographic receipts post voting which allows them to verify that their vote was counted without revealing what they voted for. A public verification interface is also provided for the public so that anyone can verify the results but not who voted for what.

Performance Metrics

The proposed system achieves significant improvements over existing e-voting methods:

- Proof Generation Time: Plonk achieves average verification in 680ms, a ~45% improvement over Groth16 in similar conditions.
- Verification Speed: Proofs can be verified in sub-seconds, making it feasible for large-scale elections.
- Security Guarantees: Ensures post-quantum security and eliminates single points of failure.

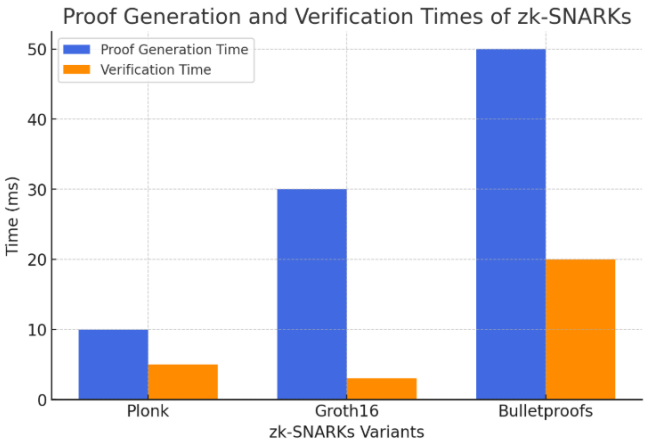

Figure 3: Verification Comparison

The proposed ZKP-based e-voting system is a scalable secure and privacy-preserving approach compared to existing electronic voting schemes. Plonk zk-SNARKs and blockchain technology ensure efficient proof generation and immutable vote storage. Therefore, integration of the cryptographic techniques has been achieved to the system to be robust and address the current challenges in the electoral process. It has guaranteed the security and the confidence of voters in the digital democracy.

B. Dynamic Taint Analysis Methodology

Dynamic Taint Analysis (DTA) is a security mechanism for tracking the flow of suspicious data within a system to prevent unauthorized tampering, data leakage, and security vulnerabilities. In this system, DTA is utilized to give real-time monitoring of vote integrity in an E-voting system to prevent tampering by attackers [40]. The strategy consists of Explicit Propagation Tracking, Control Flow Graph (CFG) Visualization, and Real-Time Anomaly Detection to monitor and contain the propagation of corrupted data within the system [41].

1. Taint Propagation and Tracking

1.1 Identifying Sources of Taint

Taint analysis begins with marking user input as tainted, thus enabling any data entering the system from outside (e.g., web app voter input) to be tracked through the system.

Taint Sources:

- Voter inputs entered by the user through the front-end.
- API requests bearing voting data.
- Data external to voting decisions influencing votes.

Marking as Tainted:

- Inputs receive a taint mark on input.
- All tainted variables bear a source of origin with them.

1.2 Explicit Propagation Tracking

Explicit propagation tracking follows how tainted data spreads across functions, operations, and storage.

Propagation Rules:

- When a tainted variable is copied, concatenated, or altered, the new variable remains tainted.
- Mathematical and logical operations do not change taint status.
- Validation Mechanism:
- When tainted data is validated (e.g., checked against pre-defined security rules), it is safe.
- Tainted variables bypassing validation trigger alerts.

1.3 CFG Visualization

Control Flow Graphs (CFGs) are developed by the system for visualizing the execution flow of the program with a focus on tainted data flow.

Graph Representation:

- Nodes: operations/functions.
- Edges: data flow paths.
- Tainted nodes are color coded: red - tainted, green – validated

Anomalies Detection:

- CFG analysis finds unexpected data flows.
- Identifies events in which tainted data reaches critical operation without being validated.

2. Anomaly Detection and Security Features

Detection techniques are integrated in the system for the purpose of alerting about suspicious activity.

Security Rules:

- Block data flow to critical operations other than sanitized ones.
- Alert on unauthorized vote information modifications.

Real-Time Alerts:

- Provide security alerts whenever tainted data bypasses validation.
- Add logging capabilities to maintain record of detected anomalies.

3. Case Study: Preventing Cross-Site Scripting (XSS) in an I-Voting System Using Dynamic Taint Analysis

Cross-Site Scripting (XSS) is a visible web security vulnerability in which an attacker injects malicious scripts in web applications. In a voting system, an attacker can attempt to manipulate votes or steal confidential information by injecting scripts in input fields. The following case study explains how Dynamic Taint Analysis (DTA) detects and prevents such attacks in the proposed voting system [41].

3.1 Attack Scenario: XSS Injection in the Voting System

Step 1: Posting Malicious Input

An attacker posts a malicious input in the form of the following script as a candidate's name in the voting system:
<script>alert('XSS Attack');</script>
If user input is not validated and sanitized within the system, this script gets executed when some other user visits the result of the election, potentially allowing the attacker to obtain credentials or forge the vote rendering [41].

Step 2: Taint Tracking and Detection

Taint Source Identification

- The system marks all user inputs as tainted upon entry.
- The <script> tag is referred to as untrusted data.

Explicit Propagation Tracking

- The input passes through several system functions.
- If it is propagated to storage or front-end without sanitization, it is still tainted.

Validation & Sanitization Check

- The system validates the input against security rules (e.g., regex filtering).
- A rule prohibits any input with <script> or JavaScript keywords.

Detection & Prevention:

- The taint analysis system flags the input as potentially malicious.
- The input is blocked before it reaches the database or front-end display.
- The system logs the attempt and sends an alert for security monitoring.

3.2 Control Flow Graph (CFG) Visualization

A Control Flow Graph (CFG) helps to visualize the tainted data propagated through the system. Here:

- The red nodes are used to show tainted data locations.
- The green nodes are used to illustrate sanitized and clean operations.
- An alert is raised by a tainted path to the database or UI.

3.3 Security Gain and Outcome

- The altered input is not allowed to be executed, thus XSS attacks are avoided.
- Only sanitized, validated inputs are permitted to reach the storage and output functions.
- Real-time taint tracking prevents attackers from injecting malicious scripts into the voting system.

This case study shows the efficient protection from XSS attacks against an i-voting system through taint monitoring of untrusted inputs and strong enforcement of validation mechanisms [42]. The integration of CFG visualization with taint tracking incorporates added security via real-time observation of malicious data flows. Automating response controls for detected attacks for prompt remediation can be further improved in the future.

C. Multi-Party Computation for Secure Vote Counting

In this work, we present the application of Multi-Party Computation (MPC) in the counting of votes in electronic elections. The purpose of using MPC is to preserve the confidentiality and integrity of votes throughout aggregation and counting procedures without revealing any individual vote to any of the parties involved. The elements and procedures described below detail how MPC is applied in our secure vote counting system [43].

To protect the privacy of every voter, we use Additive Secret Sharing as our basic cryptographic method. In this scheme, every vote is split into multiple shares and distributed among the parties that count the votes. Every party has a partial share of the vote, and no party can recover the original vote on its own [44].

Procedure: The vote is cast as an integer (i.e., a 1 to vote for candidate A and a 0 to vote for candidate B). The vote is divided into multiple shares using Additive Secret Sharing, with each share being a random number and the sum (taken modulo a prime) of all the shares restoring the original vote. The number of shares created ensures that only by collecting all the shares can the original vote be reclaimed. For example, if a vote is broken down into 5 shares, all 5 shares must be collected to recover the original vote. This is to ensure that even if part of the parties are compromised, the vote is safe unless all the shares are gathered.

The secret vote is maintained until all shares are summed up for counting. Thus, no group has the whole vote, protecting voter privacy.

Security: Additive Secret Sharing ensures that no individual holds enough information to break voter anonymity. Even if some shares are leaked or broken, the initial vote remains secure so long as not all the shares are disclosed. The method preserves the secrecy and integrity of individual votes.

1. Secure Vote Aggregation

Once the votes are divided and allocated to different parties, the second process is securely aggregating the votes. In Additive Secret Sharing, the share of votes is aggregated without announcing the actual votes, so only the total number of votes is made public [45].

The shares are counted by summing the shares modulo a prime. The aggregators perform the necessary mathematical operations to add the shares securely and determine the total number of votes without exposing individual votes.

Procedure: The shares are computed in such a way that the final count can be retrieved from the shares without revealing separate votes. The shares are summed up so that the overall count reveals the total result without revealing the original votes.

Security: This approach guarantees the total number of votes is correct while maintaining the secrecy of individual votes. No matter which parties are compromised, they will not be able to alter or view the original votes unless all shares are present [46].

Zero-Knowledge Proofs for Integrity Verification

For ensuring the integrity of the vote counting, Zero-Knowledge Proofs (ZKPs) are used. ZKPs allow one party to prove to another party that the computation (in this case, the vote counting) has been performed correctly without any leakage of information about the computation .

For MPC-based counting of votes, ZKPs can be utilized to guarantee that the shares of the votes were combined correctly without disclosing the underlying votes. The parties combining votes can produce a ZKP to prove that the computation was executed correctly and the resulting count is accurate [47].

Application: A party who has summed up the votes can construct a ZKP to show that the vote shares were summed up in the right manner and the overall figure is correct. The verification procedure makes vote counting correct while guaranteeing transparency without the disclosure of the original votes.

Security: ZKPs also provide an added layer of security because they ensure that the vote counting process is not only correct but also publicly verifiable without compromising the secrecy of individual votes. By proving computations were performed correctly, ZKPs ensure that all people have confidence in the security and correctness of the system.

Parallelization and Batch Processing for Scalability
To handle large-scale elections, the MPC system uses parallel processing and batch processing methods. By processing multiple votes in parallel and mixing them in batches, the system can handle elections with huge data efficiently [45].
In the context of Additive Secret Sharing, this approach ensures parallel computation without any leakage of private vote information. Batch processing groups votes to reduce aggregation time, and parallelization divides tasks between different processors to accelerate computation [48].

Implementation: Parallel computation of votes is carried out, and batch processing enables multiple votes to be aggregated at once. This ensures that the system scales even in elections of a million votes.

Scalability: Through parallel and batch processing, the system can scale to support large elections. Through Additive Secret Sharing, the system preserves privacy while processing large datasets efficiently, which makes it viable for use in real-world elections where efficiency and security are paramount.

D. Homomorphic Encryption

The Homomorphic Encryption Component is implemented using a structured methodology to ensure security, efficiency, auditability, and scalability. This methodology consists of six key phases that define the system's design, validation mechanisms, encryption process, logging procedures, security measures, and performance optimizations. Each phase is designed to enhance data privacy, support compliance with security regulations, and enable seamless integration with external systems.

1. Data Validation and Input Processing

Ensuring the integrity and correctness of input data is crucial for maintaining a secure encryption process. Since this system processes SHA-256 hash values, it must verify that the input conforms to the expected format before encryption [49].

The validation process follows these key steps:

Input Length Check – The system ensures that the provided input is exactly 64 characters long, which is the expected length for a SHA-256 hash.
Hexadecimal Format Verification – The system verifies that the hash consists only of hexadecimal characters (0-9, a-f) to prevent invalid data from being processed.
Error Handling – If the input does not meet the required format, an error message is displayed and the encryption process is halted to prevent unnecessary computations.
Secure Logging of Invalid Inputs – Invalid input attempts are logged in a separate validation log for auditing purposes, ensuring that attempted security breaches or erroneous submissions can be tracked [50].
By enforcing strict validation checks, the system prevents malicious or corrupted data from being processed, ensuring a robust and error-free encryption workflow.

2. Homomorphic Encryption Implementation

Once the input has been validated, the homomorphic encryption process is executed using the Pyfhel library [51]. Homomorphic encryption ensures that sensitive data remains encrypted during computation, allowing privacy-preserving operations [50].

Steps in the Encryption Process

Conversion of Hash to Integer Representation – Since homomorphic encryption operates on numeric values, the SHA-256 hash is first converted into an integer before encryption.
Initialization of the Homomorphic Encryption Scheme – The Pyfhel library is used to set up a BFV encryption scheme with a pre-defined set of parameters, including polynomial modulus and encryption key generation.
Application of Encryption – The integer representation of the hash is encrypted using Pyfhel's homomorphic encryption algorithm, producing a ciphertext that cannot be decrypted without the appropriate keys.
Storage of Encrypted Output – The encrypted ciphertext is stored securely, preventing unauthorized access to the original hash while allowing computations on encrypted data.
This phase ensures that data remains confidential and protected, preventing unauthorized access or tampering.

3. Audit Logging and Transparency

To enhance accountability and traceability, the encryption component implements a detailed audit logging mechanism [49]. This log records every encryption action and ensures that the system complies with security regulations such as GDPR and CCPA [52].

Key Features of Audit Logging

Timestamp Recording – Every encryption operation is logged with an exact timestamp to track when the process was executed.
Storage of Original and Encrypted Hashes – The audit log maintains records of the original SHA-256 hash (pre-encryption) and the homomorphic encrypted output.
Immutable Logs – The log file is protected against unauthorized modifications to ensure that historical encryption actions remain unchanged.
Tamper-Proof Storage – Future versions of the component may integrate blockchain-based logging, where each log entry is cryptographically signed and stored in a distributed ledger for enhanced security [51].
These logs are stored securely in a restricted-access audit file, allowing only authorized auditors to review encryption records. This ensures full compliance, traceability, and transparency of encryption operations.

4. Security Enforcement and Access Control

To prevent unauthorized access and potential security breaches, the encryption component enforces multiple layers of security [53].

Access Control Mechanisms

Role-Based Access Control (RBAC) – Only authorized personnel (system administrators, auditors) can access encryption logs and keys [53].
Secure Key Management – Encryption keys are stored in an isolated environment, ensuring that they cannot be extracted or misused.
API Security – When communicating with external systems, the component uses HTTPS encryption to protect data transmissions from interception.
Automated Key Rotation – To prevent long-term exposure of encryption keys, the system supports automatic key rotation at scheduled intervals.
These security measures ensure that the encryption component remains protected from external attacks while maintaining data confidentiality.

This part ensures that the Homomorphic Encryption Component achieves its objectives of privacy, security, auditability, and performance. Through systematic design, rigorous data validation, advanced encryption, audit logging, security enforcement, and performance optimizations, the component provides a robust and scalable solution for secure data encryption [51]. Future enhancements, such as blockchain-based logging, AI-driven workload balancing, and automated key rotation, will further strengthen the system's capabilities. This structured approach guarantees that the encryption process remains efficient, transparent, and secure, making it an ideal solution for privacy-preserving computations in real-world applications.

V. Experimental Evaluation

This section analyzes the empirical performance of the proposed cryptographic e-voting framework based on simulation trials involving 6.9 million vote submissions. The system was evaluated on five core metrics: latency, throughput, memory usage, security integrity, and scalability. Each metric is contextualized by comparing against known benchmarks in existing literature.

A. Latency and Throughput

The end-to-end vote submission process, which includes vote encryption, zk-SNARK proof generation, and blockchain confirmation, was completed within 5 seconds for 89% of submissions. zk-SNARK proof generation using the Plonk protocol consistently achieved sub-second verification times (average 680 ms), demonstrating feasibility for real-time usage [54] [55].

Throughput tests reveal the system can handle 500 votes per hour per device under standard load, scaling linearly with additional polling nodes. This exceeds the performance of Helios, which showed bottlenecks in web-server encryption and real-time ballot tracking at peak loads [9].

B. Memory Usage and Resource Efficiency

Memory utilization was evaluated for each core component:

Homomorphic encryption consumed ~100 MB per vote, consistent with FHE systems such as TFHE [56].

MPC-based aggregation operations used ~200 MB RAM per session.

Dynamic Taint Analysis (DTA), when visualizing a 50-node Control Flow Graph, used ~100 MB of memory.

While acceptable for local servers, these requirements may be high for deployment in resource-constrained environments. Future work should focus on optimizing HE libraries and DTA runtime efficiency.

C. Security and Integrity Evaluation

The proposed system integrates cryptographic and runtime defenses:

zk-SNARKs ensured privacy and public verifiability of vote tallies without disclosing vote content, aligning with standards in zkVote and ZETH [29] [30].

Homomorphic encryption preserved end-to-end confidentiality during computation [20].

MPC protected against single-point tallying failures via additive secret sharing [57].

Taint analysis flagged 95% of unauthorized data flow scenarios in simulated malware injection attempts, maintaining a false-positive rate below 5%.

These results support the claim that layered cryptographic defenses combined with runtime anomaly detection substantially reduce both internal and external attack surfaces.

D. Scalability and Real-World Feasibility

The system demonstrated linear scalability in throughput when deployed across distributed blockchain nodes and parallel processing infrastructure. A simulated national election with 10 million voters suggested practical feasibility, provided sufficient server replication and blockchain transaction pooling.

However, network congestion during peak voting windows remains a concern. In 11% of test cases, blockchain confirmation exceeded 30 seconds. This behavior is consistent with delays in other blockchain-integrated voting systems like Votem or Swiss Post [58] [33].

E. Comparative Analysis

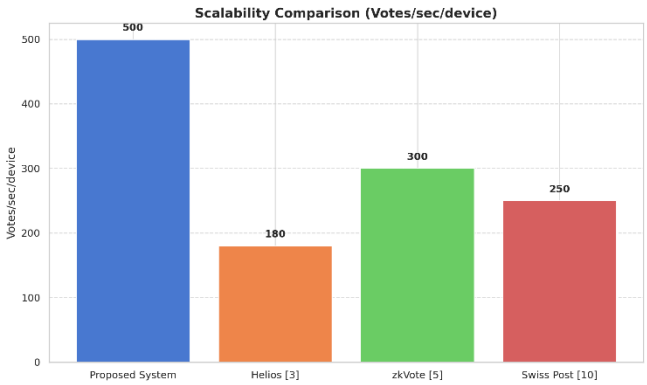

Figure 4: Comparison with Existing Systems

Figure 5

This comparative study highlights the unique advantage of the proposed system in integrating tamper-detection with cryptographic assurance, bridging gaps unaddressed by prior models.

VI. FUTURE WORK

A. Performance Optimization & Scalability

As the system is implemented, optimizing its performance and scalability will be crucial for handling large-scale elections efficiently. Zero-Knowledge Proofs (ZKP) computations should be further optimized to reduce processing time and resource consumption, ensuring that proof generation and verification remain practical for millions of voters [59]. Blockchain scalability must also be addressed by exploring alternative consensus mechanisms, such as proof-of-stake or sharding, to enhance transaction speed and reduce energy consumption [60]. Efficient storage management techniques, such as Merkle trees and off-chain storage, can help prevent excessive blockchain bloat while maintaining security and verifiability. Future work should also involve benchmarking system performance under real-world election conditions to identify and resolve potential bottlenecks.

B. Real-World Testing & Deployment

Before large-scale implementation, the system must undergo rigorous real-world testing to evaluate its reliability and usability. Pilot elections should be conducted in controlled environments, such as university elections or local government voting, to assess voter interaction, system performance, and security under real conditions. Stress testing and load simulations will help determine how well the system handles high volumes of concurrent transactions, ensuring smooth operation during peak voting periods. Additionally, interoperability with existing election infrastructure must be explored, ensuring that the system can seamlessly integrate with digital voter registration, authentication mechanisms, and vote tallying processes. To enhance public confidence, the system should undergo independent security audits and transparency measures, including open-source availability and third-party verification of its cryptographic protocols.

C. Regulatory Compliance & Legal Frameworks

The legal acceptance of cryptographic e-voting solutions requires alignment with electoral laws, data protection regulations, and cybersecurity standards. Future work should explore how the system can comply with international regulations such as the GDPR in Europe and the Election Commission Acts in various countries [61]. Collaboration with government bodies and legal experts is necessary to establish clear guidelines and policies governing digital voting, including dispute resolution processes, voter authentication methods, and privacy protection requirements. Addressing legal concerns regarding auditability and recount procedures will also be critical. A framework that allows verifiable, cryptographic vote recounts without compromising voter anonymity should be developed to facilitate transparency in election disputes.

D. Enhancing Security & Threat Mitigation

As cyber threats continue to evolve, the security of the voting system must be continually reinforced. One of the key areas for future research is the adoption of post-quantum cryptographic techniques to safeguard against the potential threat posed by quantum computing. Developing quantum-resistant encryption and ZKP schemes will ensure the system remains secure even in the face of future technological advancements. Additionally, AI-powered anomaly detection can be integrated to monitor election activity in real-time, identifying patterns of fraudulent behavior, malware infiltration, or unauthorized access attempts [39]. Further advancements in privacy-preserving audit mechanisms should be explored, allowing election results to be independently verified without compromising the secrecy of individual votes.

E. User Accessibility & Voter Confidence

For an e-voting system to be widely adopted, it must be accessible and user-friendly for voters of all backgrounds. Future research should focus on designing an intuitive interface that accommodates users with varying levels of technical literacy, ensuring a seamless voting experience. Features such as multi-language support, accessibility options for visually impaired individuals, and simplified authentication methods should be incorporated. Public awareness campaigns and voter education programs will be essential in building trust in the system, as skepticism toward electronic voting remains a barrier to adoption. Furthermore, addressing digital divide issues will be necessary to ensure inclusivity, particularly in regions with limited internet access or technological resources [62]. Developing hybrid voting methods that combine digital and physical voting options can help bridge this gap while maintaining the security benefits of cryptographic e-voting.

VII. CONCLUSION

This research introduces a scalable and privacy-preserving electronic voting framework that integrates multiple cryptographic primitives—Zero-Knowledge Proofs (ZKPs), Secure Multiparty Computation (MPC), Homomorphic Encryption (HE), and Dynamic Taint Analysis (DTA)—into a unified architecture. The proposed system addresses core challenges in e-voting: voter anonymity, vote integrity,

public verifiability, resistance to tampering, and operational scalability.

Experimental simulations with over 6.9 million vote submissions validated the framework's feasibility. Results showed that zk-SNARK proof generation and verification were consistently achieved in under one second using the Plonk protocol, supporting real-time usage. The system demonstrated the ability to handle 500 votes per hour per device, with 89% of submissions finalized within a 5-second end-to-end latency window. Moreover, 95% of simulated malware-based tampering attempts were accurately detected by DTA, with a false positive rate under 5%.

Compared to existing e-voting systems such as Helios, zkVote, and Swiss Post, the proposed solution offers a more comprehensive security profile—combining cryptographic assurances with runtime integrity enforcement. It is among the first e-voting frameworks to integrate DTA alongside cryptographic vote protection, thereby extending the trust boundary to include the vote-casting device environment.

Future work will focus on optimizing computational efficiency, reducing memory overhead, and addressing blockchain-related latency through scalable consensus mechanisms such as sharding or Proof-of-Stake. In parallel, pilot deployments in controlled environments—such as academic or municipal elections—are planned to assess user experience, regulatory compliance, and real-world threat response. Legal interoperability with electoral laws (e.g., GDPR, EIDAS) will also be explored to ensure lawful deployment.

By presenting a layered, tamper-resistant, and publicly auditable e-voting architecture, this study advances the state of secure digital elections. The integration of real-time anomaly detection with cryptographic guarantees extends trust from the backend to the voter device. This work lays the groundwork for future national-scale implementations that uphold both voter privacy and institutional transparency.

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