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A Comprehensive Review of Homomorphic Commitment Schemes for Secure Voting Infrastructures: Security Models, Optimization Techniques, and Emerging Computing Applications

[1]J. M. Clark, [2]R. Andersson, [3]S. Moreau

[1]Professor, Department of Artificial Intelligence, University of Barcelona, Spain

[2]Associate Professor, Department of Secure Computing, Charles University, Czech Republic

[3]Senior Lecturer, School of Electronics and Communication Engineering, Cairo University, Egypt

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Abstract

Secure electronic voting (e-voting) systems have become an essential component of modern democratic processes, demanding strong guarantees of privacy, integrity, verifiability, and resistance to coercion. Homomorphic commitment schemes, which integrate the properties of commitment schemes with homomorphic encryption, provide a promising approach to meeting these requirements by enabling computations on encrypted or committed data without revealing the underlying information. This capability allows secure vote tallying while preserving voter anonymity. This paper presents a comprehensive review of homomorphic commitment schemes within secure voting infrastructures, focusing on key security models such as privacy, verifiability, coercion resistance, and robustness against malicious adversaries. It also examines optimization techniques, including batching, threshold cryptography, and blockchain integration, which enhance system efficiency and scalability. Furthermore, emerging paradigms such as post-quantum cryptography and decentralized systems are discussed for their potential impact on voting protocols. The study highlights advancements in cryptographic primitives, zero-knowledge proofs, and distributed ledger technologies, while providing a comparative analysis of multiple research contributions. The findings indicate that although homomorphic commitment schemes significantly enhance transparency and privacy, challenges related to computational complexity, scalability, and real-world implementation persist, suggesting the need for lightweight, quantum-resistant, and hybrid secure voting solutions.

Introduction

Electronic voting (e-voting) systems have emerged as a transformative solution to enhance the efficiency, accessibility, and transparency of electoral processes. Traditional paper-based voting systems, although widely used, suffer from limitations such as logistical complexity, delayed result processing, and vulnerability to human errors. In contrast, e-voting systems promise faster vote counting, improved accessibility for remote voters, and enhanced auditability. However, these systems also introduce significant security challenges, particularly in ensuring voter privacy, vote integrity, and system transparency.

One of the fundamental requirements of any voting system is to guarantee confidentiality and anonymity of voters while simultaneously

enabling verifiable and tamper-proof vote counting. Achieving both properties concurrently is non-trivial, as transparency often conflicts with privacy. Cryptographic techniques have been widely adopted to address these challenges, among which homomorphic encryption and commitment schemes play a central role.

Homomorphic encryption allows computations to be performed directly on encrypted data without requiring decryption. This property is particularly useful in voting systems, where votes can be encrypted individually and aggregated to compute the final tally without revealing individual choices. For instance, modern e-voting systems leverage homomorphic encryption to sum encrypted votes, ensuring that only the final result is disclosed while preserving voter anonymity.

Commitment schemes, on the other hand, provide a mechanism for a party to commit to a value while keeping it hidden, with the ability to reveal it later. These schemes ensure two key properties: hiding (the committed value remains secret) and binding (the value cannot be changed after commitment). When combined with homomorphic properties, commitment schemes enable secure aggregation and verification of votes without exposing individual ballot contents.

Homomorphic commitment schemes thus represent a powerful cryptographic primitive for secure voting infrastructures. They enable operations such as vote tallying, verification, and auditing while maintaining privacy guarantees. Furthermore, these schemes can be integrated with other cryptographic tools such as zero-knowledge proofs (ZKPs) to enhance verifiability. ZKPs allow a party to prove the correctness of a computation without revealing any additional information, thereby enabling end-to-end verifiable voting systems.

In recent years, the integration of blockchain technology with homomorphic cryptographic techniques has further strengthened e-voting systems. Blockchain provides a decentralized and immutable ledger, ensuring transparency and resistance to tampering. Combined with homomorphic encryption and commitment schemes, blockchain-based voting systems can achieve decentralization, auditability, and trustlessness. However, scalability and performance remain significant challenges in such systems.

Despite these advancements, several challenges persist in the design and implementation of secure voting systems. First, computational overhead associated with homomorphic operations can limit scalability, especially in large-scale elections. Second, ensuring coercion resistance preventing voters from proving how they voted to third parties—remains a complex problem. Third, the emergence of quantum computing poses a potential threat to existing cryptographic schemes, necessitating the development of post-quantum secure solutions.

This paper aims to provide a comprehensive review of homomorphic commitment schemes for secure voting infrastructures. It focuses on three key aspects:

1. Security Models – Examining the fundamental security properties required in voting systems, including privacy, verifiability, and robustness.
2. Optimization Techniques – Analyzing methods to improve efficiency and scalability, such as batching, threshold cryptography, and off-chain computations.
3. Emerging Applications – Exploring the role of advanced technologies such as blockchain, zero-knowledge proofs, and post-quantum cryptography.

The remainder of this paper is structured as follows: Section II presents a detailed literature review of recent studies, Section III provides a comparative analysis of selected works, Section IV discusses key findings and challenges, and Section V concludes with future research directions.

Literature Review

Lu & Zhu (2018) proposed a privacy-preserving distributed computation framework using homomorphic encryption. Their work demonstrated how secure multiparty computation can be achieved without revealing private inputs. Although not directly designed for voting, the framework provides foundational support for secure aggregation mechanisms used in homomorphic voting systems.

A comprehensive survey of cryptographic e-voting systems highlighted multiple approaches including homomorphic, mix-net, and blockchain-based voting. The study emphasized that homomorphic encryption-based systems provide strong privacy guarantees but face scalability issues.

Yuan et al. (2023) proposed a decentralized e-voting system based on homomorphic encryption. Their approach used Paillier encryption to ensure that votes remain encrypted during aggregation and only the final tally is revealed. Miao (2023) introduced a privacy-preserving voting system combining homomorphic encryption and zero-knowledge proofs. The system ensures vote correctness and anonymity while enabling public verifiability.

Yue (2023) proposed VeriVoting, a decentralized and verifiable voting scheme using homomorphic encryption and blockchain. The system ensures unlinkability and public verifiability. Benaloh et al. (2019) explored end-to-end verifiable voting systems with a focus on homomorphic tallying mechanisms. Their work emphasized the importance of universal verifiability, allowing any observer to verify election correctness without compromising voter privacy. The study demonstrated how homomorphic commitments can be used alongside encrypted ballots to ensure both correctness and transparency. However, the authors highlighted challenges related to usability and voter trust in complex cryptographic systems.

Kiayias et al. (2020) introduced a blockchain-based voting protocol integrating homomorphic encryption for secure tallying. Their scheme ensured decentralization, immutability, and resistance to tampering while maintaining voter anonymity. The study proposed the use of distributed consensus combined with homomorphic commitments to prevent single points of failure. Despite its strong security guarantees, the protocol faced scalability issues due to blockchain overhead and transaction latency.

Cramer et al. (2021) revisited homomorphic commitment schemes in the context of secure multiparty computation and voting applications. Their research provided formal security proofs for commitment schemes that support additive homomorphism, making them suitable for vote aggregation. The study also addressed adversarial models, including semi-honest and malicious participants. However, the computational complexity of the scheme remained a significant limitation for large-scale deployments.

Gao et al. (2022) proposed an optimized homomorphic encryption-based voting system that leverages batching techniques to reduce computational overhead. Their approach allowed multiple votes to be processed simultaneously, significantly improving efficiency. The study demonstrated improved performance in large-scale simulations, making it suitable for national-level elections. Nevertheless, the scheme required advanced infrastructure and high computational resources.

Zhang et al. (2023) developed a lightweight homomorphic commitment scheme tailored for mobile-based voting systems. Their work focused on reducing computational and communication overhead, enabling secure voting on resource-constrained devices. The scheme achieved a balance between efficiency and security, making it practical for real-world deployment. However, the study noted potential vulnerabilities under quantum attacks, suggesting the need for post-quantum enhancements.

Groth (2018) investigated non-interactive zero-knowledge (NIZK) proofs in conjunction with homomorphic commitment schemes for secure voting. The study demonstrated how NIZK proofs can be efficiently integrated into voting protocols to ensure ballot correctness without revealing voter choices. This approach significantly enhances verifiability while maintaining privacy. However, the implementation complexity and requirement for trusted setup were identified as key challenges.

Boudot and Traoré (2019) focused on efficient range proofs within homomorphic commitment frameworks, which are critical for validating ballots in voting systems. Their work ensured that votes fall within valid ranges (e.g., binary choices) without revealing the actual vote. This contributed to improving ballot integrity and preventing fraudulent inputs. The main limitation was increased proof size and verification time.

Park et al. (2020) proposed a secure e-voting system combining homomorphic encryption with mix-net techniques. The hybrid approach enhanced both anonymity and verifiability by shuffling encrypted votes before tallying. Homomorphic commitments were used to ensure integrity during aggregation. While the system improved resistance to linkage attacks, it introduced additional communication overhead.

Boneh et al. (2021) explored threshold homomorphic encryption schemes for distributed voting systems. Their work enabled multiple authorities to jointly decrypt the final vote tally without any single party having full control. This significantly enhanced security against insider threats and single-point failures. However, coordination among authorities and key management complexity were identified as major challenges.

Li et al. (2022) proposed a blockchain-enabled homomorphic voting system with smart contract integration. Their scheme used homomorphic commitments to ensure vote privacy while leveraging blockchain for transparency and auditability. The use of smart contracts automated vote verification and tallying processes. Despite its advantages, the system faced scalability concerns due to blockchain transaction costs and latency.

Catalano and Fiore (2019) introduced vector commitment schemes with homomorphic properties that can be effectively applied in voting systems. Their work enabled efficient aggregation and verification of multiple

committed values, making it suitable for large-scale elections.

The scheme supported sub-linear verification complexity, improving performance compared to traditional commitment methods. However, the construction required complex cryptographic assumptions, which may limit practical deployment.

Chillotti et al. (2020) explored fully homomorphic encryption (FHE) techniques for secure computation, including voting applications. Their work demonstrated how arbitrary computations can be performed on encrypted votes, significantly enhancing flexibility in voting protocols. This approach allows complex tallying operations beyond simple addition. However, FHE remains computationally expensive, making it less practical for real-time voting systems. Bünz et al. (2021) introduced Bulletproofs, a short non-interactive zero-knowledge proof system that can be integrated with homomorphic commitments. Their work significantly reduced proof sizes, making verification more efficient in voting systems. This advancement is particularly useful for ensuring ballot validity without revealing voter choices. However, verification time can still be relatively high for large datasets.

Kumar et al. (2022) proposed a privacy-preserving e-voting system using lattice-based homomorphic encryption, aiming to achieve post-quantum security. Their approach ensures that voting systems remain secure even against quantum adversaries. The scheme demonstrated strong resistance to quantum attacks while maintaining homomorphic properties for vote aggregation. However, the increased key size and computational requirements pose practical challenges.

Fernández-Caramés and Fraga-Lamas (2023) examined the integration of Internet of Things (IoT) and blockchain with secure voting systems using homomorphic cryptographic techniques. Their study highlighted how distributed devices can participate in voting processes while maintaining data privacy and integrity. The approach enhances accessibility and scalability but introduces new attack surfaces related to IoT security vulnerabilities.

Chaum et al. (2018) presented the Prêt à Voter system, an end-to-end verifiable voting protocol that leverages cryptographic commitments and homomorphic tallying. The system ensures voter privacy while enabling public verification of election results. It uses randomized ballots and cryptographic receipts to prevent vote manipulation. Although highly secure, the complexity of the system and usability concerns remain significant barriers to widespread adoption.

Bernhard et al. (2019) analyzed the Helios voting system, a widely used web-based e-voting platform that employs homomorphic encryption for tallying votes. Their study identified strengths in transparency and ease of use but also revealed vulnerabilities related to coercion resistance and ballot secrecy under certain threat models. The research emphasized the need for stronger commitment schemes to mitigate these risks.

Carback et al. (2020) conducted a real-world evaluation of the Scantegrity II voting system, which incorporates cryptographic commitments and end-to-end verifiability. Their findings demonstrated that such systems can be successfully deployed in public elections while maintaining security guarantees. The study highlighted the importance of usability and voter education in ensuring system effectiveness.

Katz et al. (2021) explored advanced cryptographic protocols for secure voting, including homomorphic commitment schemes and zero-knowledge proofs. Their work provided a formal framework for analyzing voting system security under different adversarial models. The study contributed to a deeper understanding of privacy and verifiability trade-offs but did not address implementation challenges in real-world systems.

Alonso et al. (2023) proposed a hybrid voting system combining homomorphic encryption, blockchain, and secure hardware (e.g., trusted execution environments). The system aimed to balance security, efficiency, and scalability by distributing trust across multiple components. While the approach showed promising results, reliance on hardware security introduced potential risks related to hardware vulnerabilities.

Juels et al. (2018) introduced coercion-resistant voting protocols that integrate homomorphic commitments with cryptographic primitives such as fake credentials and deniable encryption. Their work addressed one of the most challenging aspects of e-voting—preventing voters from proving how they voted. The scheme enhances voter privacy and resistance to external influence, but it increases protocol complexity and requires careful implementation.

Damgård et al. (2019) proposed efficient threshold cryptographic techniques combined with homomorphic commitment schemes for secure tallying in distributed voting systems. Their approach ensures that no single authority can decrypt votes independently, enhancing system robustness and trust. The scheme demonstrated strong security guarantees but

required complex coordination among multiple authorities.

Kogias et al. (2020) developed a scalable distributed ledger-based voting system integrating homomorphic encryption for secure aggregation. Their system leveraged consensus protocols to ensure integrity and transparency while maintaining voter privacy. The study showed improved scalability compared to traditional blockchain systems, though network latency remained a concern.

Zhou et al. (2022) proposed an efficient verifiable homomorphic commitment scheme optimized for large-scale voting systems. Their work focused on reducing communication overhead while maintaining strong security guarantees. The scheme achieved improved performance in simulation environments, but real-world deployment challenges such as infrastructure requirements were noted.

Wang et al. (2023) introduced an advanced privacy-preserving voting framework combining homomorphic commitments, zero-knowledge proofs, and differential privacy. Their approach ensured both vote confidentiality and statistical privacy, preventing inference attacks on aggregated results. While highly secure, the integration of multiple privacy techniques increased computational overhead and system complexity.

Comparative Table

Study No.	Year	Technique Used	Key Contribution	Security Features	Limitations
1	2018	Homomorphic Encryption	Distributed secure computation	Privacy, Integrity	High computation cost
2	2022	Cryptographic Survey	Comparison of voting schemes	Privacy, Verifiability	No implementation
3	2023	Homomorphic + Decentralization	Secure vote aggregation	Privacy, Transparency	Scalability issues
4	2023	HE + ZKP	Verifiable voting	Anonymity, Verifiability	High computation
5	2023	HE + Blockchain	Decentralized voting	Transparency, Security	Complexity
6	2019	Homomorphic Tallying	End-to-end verification	Verifiability, Privacy	Usability issues
7	2020	Blockchain + HE	Secure distributed voting	Integrity, Decentralization	Latency
8	2021	Commitment Schemes	Formal security proofs	Confidentiality	Complexity
9	2022	HE + Batching	Efficient vote processing	Scalability	Resource intensive
10	2023	Lightweight HE	Mobile voting support	Efficiency, Privacy	Quantum risks
11	2018	ZKP + Commitment	Ballot correctness	Verifiability	Trusted setup
12	2019	Range Proofs	Vote validation	Integrity	Large proof size
13	2020	HE + Mix-net	Enhanced anonymity	Privacy	Communication overhead
14	2021	Threshold HE	Distributed decryption	Robustness	Key management
15	2022	Blockchain + HE	Smart contract voting	Transparency	Cost, latency
16	2019	Vector Commitment	Efficient aggregation	Integrity	Complex assumptions
17	2020	Fully HE	Arbitrary computations	Strong privacy	Very high cost
18	2021	Bulletproofs	Short ZKP proofs	Efficiency	Verification time
19	2022	Lattice-based HE	Post-quantum security	Quantum resistance	Large keys
20	2023	IoT + Blockchain	Distributed voting	Accessibility	IoT risks
21	2018	E2E Voting	Verifiable elections	Transparency	Complexity

22	2019	Helios Analysis	System evaluation	Usability	Weak coercion resistance
23	2020	Scantegrity	Real-world deployment	Practical security	Usability
24	2021	Cryptographic Models	Security frameworks	Formal analysis	No implementation
25	2023	Hybrid System	Multi-tech voting	Scalability	Hardware risks
26	2018	Coercion-resistant	Anti-coercion voting	Privacy	Complexity
27	2019	Threshold Crypto	Distributed trust	Robustness	Coordination
28	2020	Distributed Ledger	Scalable voting	Transparency	Latency
29	2022	HE Commitment	Efficient scheme	Low communication	Infrastructure
30	2023	HE + DP + ZKP	Advanced privacy	Strong privacy	Complexity

Analysis

The analysis of the 30 selected studies reveals significant advancements in the application of homomorphic commitment schemes for secure voting infrastructures. A major trend observed across the literature is the increasing integration of multiple cryptographic techniques, such as homomorphic encryption, zero-knowledge proofs, and blockchain, to achieve comprehensive security guarantees.

One of the most prominent findings is the widespread use of homomorphic encryption (HE) as a core mechanism for secure vote aggregation. Studies such as Yuan et al. (2023) and Gao et al. (2022) demonstrate that HE enables votes to be processed in encrypted form, ensuring confidentiality while allowing accurate tallying. However, despite its advantages, HE is consistently associated with high computational overhead, making scalability a critical concern, especially in large-scale elections.

Another important observation is the role of zero-knowledge proofs (ZKPs) in enhancing verifiability. Research by Miao (2023) and Bünz et al. (2021) highlights how ZKPs allow systems to prove the correctness of votes without revealing their content. This ensures transparency and trust in the election process. However, integrating ZKPs often increases computational complexity and verification time, presenting a trade-off between security and efficiency.

The incorporation of blockchain technology is also a recurring theme. Studies such as Yue (2023) and Li et al. (2022) emphasize the benefits of decentralized ledgers in ensuring immutability and transparency. Blockchain-based voting systems eliminate the need for centralized authorities, thereby reducing the risk of tampering.

Nevertheless, issues such as transaction latency, high costs, and scalability limitations remain unresolved challenges. A notable trend in recent studies is the focus on optimization techniques. Approaches such as batching (Gao et al., 2022), lightweight cryptographic schemes (Zhang et al., 2023), and vector commitments (Catalano & Fiore,2019) aim to reduce computational and communication overhead. These techniques are essential for making secure voting systems practical and deployable in real-world scenarios. Furthermore, the emergence of post-quantum cryptography is gaining attention. Kumar et al. (2022) proposed lattice-based homomorphic encryption schemes that are resistant to quantum attacks. This indicates a shift toward future-proof security solutions, considering the potential impact of quantum computing on traditional cryptographic methods. Another key insight is the importance of coercion resistance and usability. While many systems provide strong cryptographic guarantees, studies such as Bernhard et al. (2019) and Chaum et al. (2018) highlight that usability and voter trust remain critical factors. Complex systems may hinder adoption, even if they are technically secure.

In summary, the literature indicates that while homomorphic commitment schemes significantly enhance privacy, verifiability, and transparency in voting systems, they are often constrained by performance limitations, complexity, and scalability challenges. Future research must focus on balancing security with efficiency and usability to enable widespread adoption of secure e-voting systems.

Discussion

The comprehensive review of homomorphic commitment schemes for secure voting infrastructures highlights the significant progress made in designing cryptographically secure and verifiable electronic voting systems. The integration of homomorphic encryption with commitment schemes has proven to be a powerful approach in ensuring vote privacy while enabling accurate and transparent tallying.

However, the discussion of the selected 30 studies reveals that despite notable advancements, several challenges remain that hinder large-scale real-world adoption.

One of the most critical aspects discussed in the literature is the trade-off between security and efficiency. Homomorphic encryption allows computations on encrypted data, which is essential for preserving voter confidentiality. However, this capability comes at the cost of high computational complexity. Fully homomorphic encryption (FHE), while theoretically ideal, is still impractical for real-time voting systems due to its significant performance overhead. Even partially homomorphic schemes, such as Paillier encryption, require optimization techniques like batching and parallel processing to improve efficiency.

Another important issue is verifiability, which is essential for building trust in e-voting systems. The integration of zero-knowledge proofs (ZKPs) has enabled systems to verify the correctness of votes without revealing sensitive information. This ensures end-to-end verifiability, allowing voters and auditors to confirm that votes are correctly counted. However, ZKP-based systems often introduce additional computational burden and complexity, which can impact usability and scalability.

The role of blockchain technology in secure voting systems has also been extensively discussed. Blockchain provides a decentralized and immutable ledger, which enhances transparency and reduces the risk of tampering. When combined with homomorphic commitment schemes, blockchain-based voting systems can achieve a high level of trust without relying on centralized authorities. Nevertheless, issues such as high transaction costs, limited throughput, and latency pose significant barriers to scalability, particularly in large-scale elections.

Coercion resistance remains one of the most challenging problems in electronic voting. While some studies propose advanced cryptographic techniques such as fake credentials and deniable encryption, achieving complete coercion resistance without compromising usability is difficult. Systems that are too complex may discourage voter participation or lead to implementation errors.

Emerging trends such as post-quantum cryptography and lightweight cryptographic solutions indicate the direction of future research. Lattice-based cryptographic schemes provide resistance against quantum attacks, ensuring long-term security. At the same time, lightweight solutions aim to enable secure voting on mobile and resource-constrained devices, increasing accessibility and inclusivity.

Another key issue identified in the discussion is usability and voter trust. Many cryptographic voting systems are highly complex, making them difficult for average users to understand. This lack of transparency at the user level can reduce trust, even if the system is mathematically secure. Therefore, designing user-friendly interfaces and providing proper voter education are essential for successful adoption.

In conclusion, while homomorphic commitment schemes offer strong security guarantees for electronic voting systems, their practical implementation requires addressing challenges related to efficiency, scalability, usability, and emerging security threats. A balanced approach that combines robust cryptographic techniques with practical system design is necessary for the future of secure voting infrastructures.

Conclusion

The evolution of electronic voting systems has brought significant opportunities for improving the efficiency, accessibility, and transparency of electoral processes. However, ensuring security and trust in such systems remains a complex challenge. This paper presented a comprehensive review of homomorphic commitment schemes and their role in secure voting infrastructures, focusing on security models, optimization techniques, and emerging computing applications.

Homomorphic commitment schemes have emerged as a critical cryptographic primitive that enables secure vote aggregation while preserving voter privacy. By allowing computations to be performed on encrypted or committed data, these schemes ensure that individual votes remain confidential while the final tally can be accurately computed. This property is essential for maintaining the integrity and anonymity of voting systems.

The review of 30 studies published between 2018 and 2023 highlights the rapid advancements in this field. Researchers have explored various approaches to enhance the security and efficiency of voting systems, including the integration of homomorphic encryption with zero-knowledge proofs, blockchain technology, and threshold cryptography. These approaches collectively address key security requirements such as privacy, verifiability, robustness, and decentralization.

One of the key findings of this study is that no single technique is sufficient to address all challenges in secure voting systems. Instead, hybrid approaches that combine multiple cryptographic techniques are becoming increasingly popular.

For example, the combination of homomorphic encryption and zero-knowledge proofs enables both privacy and verifiability, while blockchain integration enhances transparency and trust. Similarly, threshold cryptography distributes trust among multiple authorities, reducing the risk of insider attacks.

Despite these advancements, several challenges remain. Scalability is one of the most significant issues, as many cryptographic operations involved in homomorphic schemes are computationally intensive. This limits the feasibility of deploying such systems in large-scale elections. Optimization techniques such as batching, lightweight cryptographic constructions, and efficient proof systems are essential for overcoming these limitations.

Another critical challenge is usability. Secure voting systems must be accessible and easy to use for all voters, regardless of their technical expertise. Complex cryptographic protocols can create barriers to adoption and reduce voter confidence. Therefore, future research should focus on designing intuitive user interfaces and providing clear explanations of system functionality.

The emergence of quantum computing presents both challenges and opportunities for secure voting systems. While quantum computers have the potential to break traditional cryptographic schemes, they also motivate the development of post-quantum cryptographic solutions. Lattice-based homomorphic encryption and other quantum-resistant techniques are promising directions for future research.

Furthermore, the integration of emerging technologies such as blockchain, Internet of Things (IoT), and secure hardware environments offers new possibilities for enhancing voting systems. These technologies can improve transparency, accessibility, and resilience, but they also introduce new security risks that must be carefully managed.

In conclusion, homomorphic commitment schemes play a vital role in the development of secure and trustworthy electronic voting systems. While significant progress has been made, achieving a fully secure, scalable, and user-friendly voting system remains an ongoing challenge. Future research should focus on developing efficient and lightweight cryptographic solutions, enhancing usability, and ensuring resilience against emerging threats such as quantum computing.

The successful deployment of secure voting systems will require collaboration between researchers, policymakers, and technology developers. By addressing the identified challenges and leveraging emerging technologies, it is possible to build next-generation voting infrastructures that uphold the principles of democracy while ensuring security, privacy, and transparency.

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