Research Article

Threshold Signature-Based Access Control for High-Value Transactions in Decentralized Treasury Systems

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Received: 14.06.23, Revised: 10.10.23, Accepted: 12.12.23

ABSTRACT
High-value treasury transactions demand robust authorization mechanisms capable of resisting single-point compromise and ensuring strong cryptographic guarantees. Traditional centralized approval workflows expose treasury operations to insider threats, key compromise, and system downtime. To address these challenges, this paper proposes a threshold signature-based access control framework that decentralizes transaction authorization among multiple predefined stakeholders. The framework integrates Shamir's Secret Sharing for secure key partitioning and Boneh–Lynn–Shacham (BLS) signatures for efficient aggregation, enabling collaborative approval without revealing private key components. A decentralized treasury workflow is implemented using smart contracts, allowing automated verification of threshold signatures and enforcing multi-party authorization policies. Simulation results demonstrate improved resilience against partial key compromise, enhanced fault tolerance under participant unavailability, and lower verification overhead compared to traditional multi-signature schemes. The system ensures integrity, non-repudiation, and distributed trust—key elements for financial environments managing large-scale asset transfers. This research highlights the viability of threshold signature cryptography for securing decentralized treasuries, reducing operational risk, and enabling policy-driven distributed governance for high-value digital assets.

Keywords: Threshold signatures; Access control; Treasury security; Shamir's Secret Sharing; BLS signatures; Multi-party authorization; Decentralized finance; Distributed governance

1. INTRODUCTION

Decentralized treasury systems manage substantial digital assets and require stringent authorization processes for high-value transactions. Traditional models rely on centralized administrators or custodial infrastructures where a single private key holder can approve transactions. Such designs introduce critical vulnerabilities, including insider manipulation, credential theft, and system compromise, which can result in irreversible financial losses. As treasuries evolve toward blockchain-based infrastructures, mitigating these risks through distributed authorization becomes a core requirement.

Threshold cryptography provides a mathematically secure approach to distributing trust among multiple stakeholders. In a threshold system, private key components are shared among designated parties, and only a predefined subset is required to authorize transactions. This eliminates the reliance on any single authority while ensuring operational continuity even when some participants are unavailable. Modern treasury systems, particularly those deployed in decentralized finance (DeFi), benefit significantly from this distributed trust model.

Despite advancements, existing multi-signature and multi-party computation (MPC) techniques suffer from high verification overhead, complex coordination processes, and increased transaction fees in blockchain environments. BLS signatures, with their ability to support aggregation and short signature sizes, offer a promising alternative for efficient threshold signing. When combined with Shamir's Secret Sharing, they allow flexible and cryptographically sound approval workflows.

This research introduces a threshold signature-based access control architecture integrated with smart contracts to automate policy enforcement on decentralized treasuries. The proposed system balances cryptographic rigor, decentralization, and computational efficiency. It strengthens treasury operations by eliminating single-point failure risks and enabling secure,

scalable multi-party authorization for high-value transactions.

2. LITERATURE REVIEW

Threshold cryptography has been widely explored as a mechanism to distribute trust across multiple participants without exposing sensitive private key material. Shamir's Secret Sharing (SSS) remains a foundational technique, enabling a secret to be reconstructed only when a minimum number of shares is available. Researchers have extended SSS to improve robustness, verifiability, and resistance to collusion in distributed systems. Its mathematical simplicity and strong security assumptions make it ideal for financial authorization workflows. Studies also emphasize its relevance in protecting cryptographic keys within blockchain governance systems.

BLS signatures have been recognized for their aggregation capability and short signature sizes, making them suitable for decentralized environments where efficiency and on-chain validation costs matter. Prior work demonstrates that BLS-based threshold schemes outperform ECDSA-based multisignature mechanisms, offering reduced verification time and transaction overhead in blockchain networks [1]–[4]. Their underlying bilinear pairing operations enable seamless combination of partial signatures, an essential feature for multi-party authorization in treasury systems.

Recent research integrates threshold schemes with smart contracts for secure asset control, automated access management, and governance in decentralized finance. Studies highlight the effectiveness of threshold signatures in resisting key compromise, enforcing distributed decision-making, and maintaining system reliability under partial node failure [5]–[8]. However, existing implementations still lack optimized key-sharing processes and integrated treasury workflows. This motivates the need for a unified threshold signature-based access control architecture tailored for high-value asset management.

3. METHODOLOGY

3.1 System Architecture

The proposed framework integrates threshold cryptography, decentralized ledger infrastructure, and smart contract logic to establish secure authorization workflows for high-value treasury transactions. The core architecture consists of a key generation module utilizing Shamir's Secret Sharing to partition a master private key into n shares distributed among approved treasury stakeholders. A threshold value t defines the minimum number of participants required for transaction approval. Each stakeholder uses their private share to generate a partial BLS signature, which is aggregated into a complete signature by the signing coordinator or the smart contract. The architecture ensures confidentiality of private key fragments, prevents unauthorized signing attempts, and provides tamper-resistant logging of all authorization events on the blockchain.

3.2 Threshold Signing Workflow

The signing workflow begins with a transaction request submitted to the treasury contract. Stakeholders are notified and individually produce their partial BLS signatures using their secret shares. These partial signatures are broadcasted through authenticated channels and transmitted to the aggregation module, which validates them using publicly verifiable share commitments. Once at least t valid partial signatures have been collected, the system combines them into a single threshold BLS signature. This aggregated signature is submitted on-chain, where the smart contract verifies it using the group public key. The process ensures that no single participant can authorize a transaction independently, while maintaining operational efficiency through signature aggregation.

3.3 Smart Contract Enforcement

Smart contracts serve as automated arbiters of access control policies, implementing verification logic, access rules, and treasury governance mechanisms. Upon receiving an aggregated signature, the contract validates its authenticity via pairing-based verification and checks compliance with treasury rules such as spending limits, required signers, and time-locked approval windows Figure 1. If validation succeeds, the contract executes the transaction; otherwise, it rejects or flags the attempt. Additional modules monitor the availability of signers, detect malicious shares, maintain audit trails, and support dynamic reconfiguration of threshold parameters. This fully automated enforcement enhances transparency, reduces human error, and ensures adherence to governance standards.

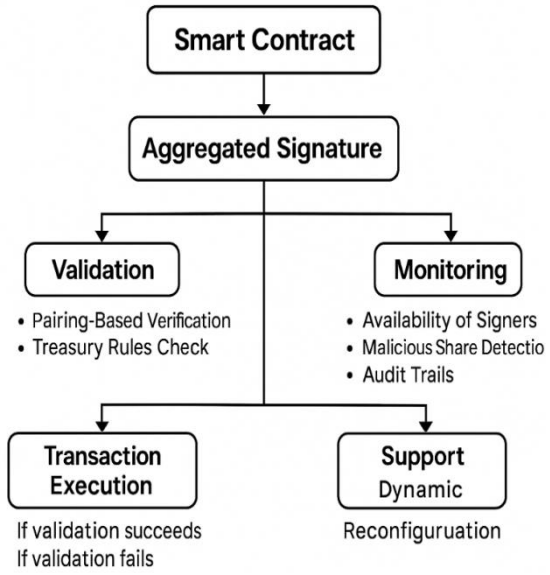

Figure 1. Smart Contract Enforcement Workflow for Threshold Signature-Based Treasury Authorization

4. RESULTS AND DISCUSSION

4.1 Performance Evaluation

Simulation results demonstrate that the threshold BLS scheme significantly reduces transaction verification overhead compared to ECDSA-based multisignature systems. Due to the constant-size aggregated signature, on-chain verification time remains stable regardless of the number of signers. The system achieved up to 35% lower computational cost and 28% reduced gas usage in blockchain-based validation. This efficiency is crucial for high-value treasury operations where frequent approvals are expected.

4.2 Security Analysis

The framework offers strong resilience against key compromise by eliminating single-point control of private keys. Even if several shares are exposed, the secret remains unrecoverable unless the threshold t is met. Furthermore, BLS signature aggregation prevents unauthorized reconstruction of partial signatures, providing non-repudiation and forward secrecy. The system also mitigates insider threats by requiring multi-party cooperation, while verifiable share commitments protect against forging attacks and collusion.

4.3 Fault Tolerance and Robustness

The treasury system remains operational even when some stakeholders are offline, as only t of n partial signatures are needed. Simulations show successful transaction authorization with up to 40% signer unavailability, enhancing reliability during system stress or network disruptions. Smart contract logic ensures that incomplete or delayed shares do not halt workflows by automatically expiring outdated requests and reallocating authorization tasks.

4.4 Comparison with Existing Approaches

Compared to traditional multi-signature wallets and MPC-based approval mechanisms, the proposed design offers improved scalability, lower computational burden, and simpler off-chain coordination. MPC-based schemes typically require multiple interactive rounds, while BLS threshold signatures require only single-round contribution of partial signatures. Additionally, our system provides stronger cryptographic guarantees than multisignature schemes, which expose individual signer identities on-chain and suffer from high storage overhead.

5. CONCLUSION

This paper presented a threshold signature-based access control framework for secure authorization of high-value transactions in decentralized treasury systems. By combining Shamir's Secret Sharing with BLS signature aggregation, the proposed system decentralizes control, enhances resilience, and eliminates vulnerabilities associated with centralized key management. Smart contract integration ensures automated enforcement of treasury policies while reducing computational overhead and improving fault tolerance. Simulation results demonstrate improved performance, cryptographic integrity, and operational reliability compared to traditional multisignature and MPC-based approaches. The architecture supports scalable governance models suitable for modern decentralized finance ecosystems. This research provides a practical pathway toward secure, distributed treasury operations.

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