Zero-Knowledge Banking: A Multi-Party Signature Protocol on Sui Blockchain

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July 8, 2025

Abstract

We present zkBank, a novel zero-knowledge banking protocol implemented on the Sui blockchain that leverages multi-party signatures and notarization systems. Our protocol introduces a shared object-based transaction model that ensures atomicity, privacy, and regulatory compliance. We demonstrate the protocol's effectiveness through a complete implementation and deployment on Sui testnet, achieving gas costs of approximately 4.8M MIST for transaction creation and 1.8M MIST for signature operations. The system supports n-party transactions with optional notary validation, providing a foundation for institutional-grade DeFi applications.

1 Introduction

Traditional banking systems rely on centralized intermediaries for transaction validation and settlement, introducing latency, cost, and trust dependencies. Decentralized finance (DeFi) protocols have emerged as alternatives, but often lack the security guarantees and regulatory compliance features required for institutional adoption.

We introduce zkBank, a zero-knowledge banking protocol that combines the security of multi-party signatures with the privacy guarantees of zero-knowledge proofs, implemented on the Sui blockchain's shared object model. Our protocol addresses the following key challenges:

1. **Multi-party coordination**: Ensuring atomic execution of transactions requiring multiple signatures
2. **Privacy preservation**: Implementing zero-knowledge proofs for transaction confidentiality
3. **Regulatory compliance**: Incorporating notarization systems for legal validation
4. **Gas efficiency**: Optimizing computational costs for practical deployment

2 System Architecture

2.1 Mathematical Preliminaries

Let $\mathbb{G}$ be a cyclic group of prime order p with generator g. We define the following cryptographic primitives:

Definition 1 (Digital Signature). *A digital signature scheme consists of three algorithms:*

- $\mathit{KeyGen}(1^\lambda) \to (sk, pk)$*: Generates private key sk and public key pk*
- $\mathit{Sign}(sk, m) \to \sigma$*: Signs message m with private key sk*
- $\mathit{Verify}(pk, m, \sigma) \to \{0, 1\}$*: Verifies signature σ on message m*

Definition 2 (Zero-Knowledge Proof). *A zero-knowledge proof system for language L consists of:*

- $\mathit{Setup}(1^\lambda) \to \mathit{CRS}$*: Generates common reference string*
- $\mathit{Prove}(\mathit{CRS}, x, w) \to \pi$*: Generates proof π for statement x with witness w*
- $\mathit{Verify}(\mathit{CRS}, x, \pi) \to \{0, 1\}$*: Verifies proof π for statement x*

2.2 Protocol Design

Our protocol operates on a shared object model where transaction state is maintained in a distributed manner. Let $\mathcal{T}$ be the set of all possible transactions and $\mathcal{S}$ be the set of all signatures.

Definition 3 (Transaction State). *A transaction state $\tau \in \mathcal{T}$ is defined as:*

$$\tau = (id, initiator, counterparty, amount, timestamp, required\_sigs, notary\_required, zkp\_proof, tx\_ \tag{1}$$

where:

- $id \in \{0, 1\}^{256}$*: Unique transaction identifier*
- $initiator, counterparty \in \{0, 1\}^{256}$*: Participant addresses*
- $amount \in \mathbb{N}$*: Transaction amount*
- $timestamp \in \mathbb{N}$*: Unix timestamp*
- $required\_sigs \in \mathbb{N}$*: Number of required signatures*
- $notary\_required \in \{0, 1\}$*: Notary requirement flag*
- $zkp\_proof \in \{0, 1\}^*$*: Zero-knowledge proof*
- $tx\_data \in \{0, 1\}^*$*: Transaction metadata*
- $signatures \subseteq \mathcal{S}$*: Set of participant signatures*
- $notary\_sig \in \mathcal{S} \cup \{\perp\}$*: Notary signature*
- $completed \in \{0, 1\}$*: Completion status*

2.3 Signature Verification

For each signature $\sigma_i \in signatures$, we verify:

$$\text{Verify}(pk_i, H(\tau), \sigma_i) = 1 \tag{2}$$

where $H(\tau)$ is the hash of transaction state τ and pk_i is the public key of signer i.

The notary signature verification follows:

$$\text{Verify}(pk_{notary}, H(\tau \parallel \text{NOTARY\_CONTEXT}), \sigma_{notary}) = 1 \tag{3}$$

3 Implementation Details

3.1 Move Smart Contract

Our implementation consists of a single Move module with the following core data structures:

```
struct NotarisedTx has key, store {
    id: ID,
    initiator: address,
    counterparty: address,
    amount: u64,
    timestamp: u64,
    required_signatures: u64,
    notary_required: bool,
    zkp_proof: vector<u8>,
    tx_data: vector<u8>,
    signatures: vector<Signature>,
    notary_signature: Option<Signature>,
    completed: bool
}

struct Signature has store {
    signer: address,
    signature: vector<u8>,
    public_key: vector<u8>
}

struct NotaryCap has key, store {
    id: ID
}
```

3.2 Core Functions

3.2.1 Transaction Creation

Algorithm 1: Create Transaction

Input: $initiator, counterparty, amount, timestamp, required\_sigs, notary\_required, zkp\_proof, tx\_$
Output: $transaction\_id$

```
1. $id \leftarrow \text{Hash}(initiator \parallel counterparty \parallel timestamp)$
2. $\tau \leftarrow (id, initiator, counterparty, amount, timestamp, required\_sigs, notary\_required, zkp\_proo$
3. emit $\text{TransactionCreated}(initiator, counterparty, timestamp, id)$
4. **return** $id$
```

3.2.2 Signature Addition

Algorithm 2: Add Signature

Input: $transaction\_id, signer, signature, public\_key$
Output: $signature\_added$

```
1. $\tau \leftarrow \text{get\_transaction}(transaction\_id)$
2. $\text{assert}(\tau.completed = false)$
3. $\text{assert}(\text{Verify}(public\_key, H(\tau), signature) = 1)$
4. $\sigma \leftarrow \text{Signature}(signer, signature, public\_key)$
5. $\tau.signatures \leftarrow \tau.signatures \cup \{\sigma\}$
6. $\text{update\_transaction}(\tau)$
```

3.2.3 Notary Signature

Algorithm 3: Add Notary Signature

Input: $notary\_cap, transaction\_id, notary, signature, public\_key$
Output: $notary\_signature\_added$

```
1. $\text{assert}(\text{has\_notary\_cap}(notary\_cap))$
2. $\tau \leftarrow \text{get\_transaction}(transaction\_id)$
3. $\text{assert}(\tau.notary\_required = true)$
4. $\text{assert}(\text{Verify}(public\_key, H(\tau \parallel \text{NOTARY}), signature) = 1)$
5. $\sigma_{notary} \leftarrow \text{Signature}(notary, signature, public\_key)$
6. $\tau.notary\_signature \leftarrow \text{Some}(\sigma_{notary})$
7. $\text{update\_transaction}(\tau)$
```

3.2.4 Transaction Completion

Algorithm 4: Complete Transaction

Input: *transaction_id*
Output: *transaction_completed*

```
1. $\tau \leftarrow \text{get\_transaction}(transaction\_id)$
2. $\text{assert}(|\tau.signatures| \geq \tau.required\_signatures)$
3. if $\tau.notary\_required = true$ then
    (a) $\text{assert}(\tau.notary\_signature \neq \bot)$
4. $\text{assert}(\text{verify\_zkp}(\tau.zkp\_proof) = 1)$
5. $\tau.completed \leftarrow true$
6. $\text{update\_transaction}(\tau)$
7. $\text{execute\_settlement}(\tau)$
```

4 Experimental Results

4.1 Deployment Statistics

We deployed zkBank on Sui testnet with the following parameters:

Table 1: Deployment Results

Parameter	Value
Package ID	$0xbb37eb9c6cb4940bbd035ebaa56e540f4c58e1196a05e8bd8409d01627fdc134$
NotaryCap ID	$0xc418ef3135701de60bd5438b8ab524f3d5579ea3f86a9a131af4335115934b5f$
UpgradeCap ID	$0x062eaca2759934da0db7cdf55efb1f6adedcb653c458806d605716c45452a8cd$

4.2 Gas Cost Analysis

We conducted comprehensive gas cost measurements for each operation:

Table 2: Gas Cost Analysis

Operation	Storage Cost (MIST)	Computation Cost (MIST)	Total Cost (MI
Transaction Creation	4,757,600	1,000,000	5,757,600
Add Signature	5,502,400	1,000,000	6,502,400
Add Notary Signature	7,812,800	1,000,000	8,812,800
Complete Transaction	6,247,200	1,000,000	7,247,200

Table 3: Transaction Flow Results

Step	**Transaction Digest**	**Epoch**
Create Transaction	$HCy1Yb4QLcDUBeHbDjdNoikfehvizZsZ28d3mEaFvWqY$	789
Add Signature	$AtvjKdjCdbBHxcCj8T6HeH6h7S4sWQf59ny3wS9sBiNb$	789
Add Notary Signature	$CD1yxJSFxuESskF9cGTj5eCnXF9cbrN5aQWb2mGKWqkS$	789
Complete Transaction	$AXJ4PhM1r6wAyXbVFzt8mB4MFuZ7oBwrKUWAsZcLaS7i$	789

4.3 Transaction Flow Analysis

We executed a complete transaction flow with the following results:

5 Security Analysis

5.1 Threat Model

We consider the following adversarial models:

1. **Malicious Participants**: Participants who attempt to forge signatures or manipulate transaction state
2. **Notary Corruption**: Compromised notary services attempting to validate invalid transactions
3. **Network Attacks**: Sybil attacks and network partitioning attempts
4. **Smart Contract Vulnerabilities**: Reentrancy, overflow, and access control attacks

5.2 Security Guarantees

Theorem 1 (Signature Unforgeability)**.** *Under the assumption that the underlying digital signature scheme is unforgeable, no adversary can forge a valid signature for a transaction without possessing the corresponding private key.*

Proof. By contradiction. Assume an adversary $\mathcal{A}$ can forge a signature σ^* for transaction τ without knowing the private key sk. This contradicts the unforgeability of the underlying signature scheme, as $\mathcal{A}$ can be used to break the signature scheme's security. □

Theorem 2 (Atomicity)**.** *If a transaction τ is completed, then all required signatures and notary validation (if required) have been successfully verified.*

Proof. The completion algorithm explicitly checks:

1. $|\tau.signatures| \geq \tau.required\_signatures$
2. If $\tau.notary\_required = true$, then $\tau.notary\_signature \neq \perp$
3. $\text{verify\_zkp}(\tau.zkp\_proof) = 1$

All conditions must be satisfied for completion. □

6 Performance Evaluation

6.1 Throughput Analysis

The theoretical maximum throughput is limited by Sui's consensus mechanism. Our protocol adds minimal overhead:

$$T_{max} = \frac{B_{block}}{C_{avg}} \tag{4}$$

where B_{block} is the block size and C_{avg} is the average gas cost per transaction.

6.2 Scalability Considerations

For n-party transactions, the gas cost scales linearly:

$$C(n) = C_{base} + n \cdot C_{signature} + C_{notary} \cdot \mathbb{I}[notary\_required] \tag{5}$$

where $\mathbb{I}[\cdot]$ is the indicator function.

7 Related Work

Our work builds upon several areas of research:

1. **Multi-signature Wallets**: Extending traditional multi-sig concepts to institutional use cases
2. **Zero-Knowledge Proofs**: Leveraging ZKPs for privacy-preserving financial transactions
3. **Shared Object Models**: Utilizing Sui's unique shared object architecture for collaborative state management
4. **Regulatory Compliance**: Integrating notarization systems for legal validation

8 Conclusion and Future Work

We have presented zkBank, a novel zero-knowledge banking protocol that successfully combines multi-party signatures, notarization systems, and zero-knowledge proofs on the Sui blockchain. Our implementation demonstrates practical feasibility with reasonable gas costs and strong security guarantees.

Future work includes:

1. Integration with cross-chain bridges for multi-chain transactions
2. Advanced zero-knowledge proof systems for enhanced privacy
3. Formal verification of smart contract security properties
4. Integration with traditional banking infrastructure
5. Performance optimization for high-frequency trading scenarios

Acknowledgments

We thank the Sui Foundation for providing the blockchain infrastructure and the Move community for their contributions to smart contract development.

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