Lux Z-Chain: Privacy-Preserving Smart Contracts with Zero-Knowledge Proofs

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Abstract

We present **Lux Z-Chain**, a privacy-focused Layer-2 appchain enabling confidential smart contracts via zero-knowledge proofs. Z-Chain combines **zk-SNARKs** for transaction privacy, **FHE (Fully Homomorphic Encryption)** for encrypted computation, and **TEE (Trusted Execution Environments)** for hybrid privacy guarantees. Key contributions: (i) zk-EVM with **100+ TPS** throughput for private transactions, (ii) Confidential token standard (LRC-721P) compatible with NFTs and DeFi, (iii) Privacy-preserving DeFi primitives (swap, lend, stake) with **¡ 2s finality**, (iv) Regulatory compliance via selective disclosure and auditor keys. Deployed on testnet, Z-Chain has processed **1.2M private transactions** with **zero privacy breaches**.

1 Introduction

Public blockchains expose all transaction data on-chain, creating privacy challenges for:

- **Individuals**: Wallet balances and transaction history publicly visible
- **Enterprises**: Business logic and trading strategies exposed
- **Institutions**: Regulatory compliance requires selective disclosure, not full transparency

Prior Work. Existing privacy solutions have limitations:

- **Zcash**: Privacy only for native token, no smart contracts
- **Monero**: Ring signatures have limited anonymity set
- **Aztec**: zk-Rollup has 30+ second proof generation
- **Tornado Cash**: Mixer contracts sanctioned by OFAC

Our Solution. Lux Z-Chain provides **programmable privacy** via zk-EVM, enabling private smart contracts with DeFi composability and regulatory compliance.

2 Architecture

2.1 Privacy Model

Z-Chain offers **three privacy tiers**:

Tier	Privacy Level	Technology	Use Case
Tier 0	Public	Standard EVM	Transparent DeFi
Tier 1	Shielded	zk-SNARKs	Private transfers
Tier 2	Confidential	FHE	Encrypted DeFi
Tier 3	Trusted	TEE (SGX/SEV)	Regulated finance

Table 1: Z-Chain privacy tiers and technology stack

Users select privacy tier per transaction based on requirements.

2.2 System Components

- **zk-EVM**: Zero-knowledge virtual machine for private smart contracts
- **Proof Generators**: Distributed provers generating zk-SNARKs
- **FHE Coprocessor**: Encrypted computation for Tier 2 contracts
- **TEE Validators**: SGX/SEV enclaves for Tier 3 contracts
- **Auditor Registry**: Authorized auditors with selective disclosure keys

3 zk-EVM Architecture

3.1 zkEVM Design

Z-Chain implements a **Type-3 zkEVM** (EVM-equivalent bytecode):

1. User submits shielded transaction T
2. Sequencer executes T off-chain, generates witness w
3. Prover generates zk-SNARK proof π:

$$\pi \leftarrow \text{Prove}\left(\text{ValidExec}(T, w, \text{state}_{\text{old}}, \text{state}_{\text{new}})\right) \tag{1}$$

4. L1 verifier checks π and updates state commitment

Privacy Guarantee: L1 sees only state commitment $C = \text{Hash}(\text{state}_{\text{new}})$, not transaction details.

3.2 Proof System

Circuit Constraints:

- EVM opcode execution: 2.1M constraints
- Merkle proof verification: 850k constraints
- Signature verification (ECDSA): 1.5M constraints
- Total: **4.45M constraints**

Performance:

- Proof generation: 6.8s per transaction
- Proof size: 288 bytes (Groth16)
- Verification time: 12ms on-chain
- Gas cost: 280k per proof

4 Confidential Token Standard

4.1 LRC-721P (Private NFTs)

Extension of ERC-721 with privacy:

Algorithm 1 Shielded NFT Transfer

Input: NFT ID n, recipient address A_{recv}, nullifier ν
Output: zk-SNARK proof π

// Prove ownership without revealing identity
$\text{commitment}_{\text{old}} \leftarrow \text{Hash}(n, A_{\text{sender}}, \text{salt})$
$\text{commitment}_{\text{new}} \leftarrow \text{Hash}(n, A_{\text{recv}}, \text{salt}')$

// Public inputs: $(\text{commitment}_{\text{old}}, \text{commitment}_{\text{new}}, \nu)$
// Private inputs: $(n, A_{\text{sender}}, A_{\text{recv}}, \text{salt}, \text{salt}')$

$$\pi \leftarrow \text{Prove}\begin{pmatrix} \text{commitment}_{\text{old}} \text{ in Merkle tree} \\ \wedge\ \nu = \text{Hash}(n, A_{\text{sender}}) \\ \wedge\ \text{commitment}_{\text{new}} = \text{Hash}(n, A_{\text{recv}}, \text{salt}') \end{pmatrix}$$

return π

Privacy Properties:

- NFT ownership hidden (only commitment visible)
- Transfer recipient hidden (encrypted address)
- Transfer history unlinkable (nullifiers prevent double-spend)
- Optional metadata disclosure via auditor key

5 Privacy-Preserving DeFi

5.1 Shielded DEX

Private Token Swap Protocol:

1. User deposits tokens A into shielded pool (generates commitment C_A)
2. User submits swap order $(C_A, B_{\text{amount}}, \text{price})$ via zkSNARK
3. DEX matches orders off-chain
4. User withdraws tokens B via proof π_B:

$$\pi_B \leftarrow \text{Prove}\left(\text{OwnsCommitment}(C_A) \wedge \text{ValidSwap}(A \to B)\right) \tag{2}$$

Advantages:

- Order book hidden (prevents front-running)
- Trading volume private (hides whale activity)
- Slippage protected (encrypted order matching)

5.2 Private Lending

Confidential Loan Protocol:

Action	Privacy Level
Collateral deposit	Shielded (zk-SNARK)
Loan amount	Encrypted (FHE)
Interest rate	Public (on-chain)
Liquidation threshold	Encrypted (FHE)

Table 2: Privacy levels in Z-Chain lending protocol

Key Feature: Liquidations occur via encrypted threshold checks (FHE-based), preserving collateral privacy until liquidation event.

6 Fully Homomorphic Encryption (FHE)

6.1 FHE Integration

For Tier 2 contracts, Z-Chain uses **TFHE (Threshold FHE)**:

- **Encryption**: User encrypts inputs under FHE public key
- **Computation**: Smart contract operates on ciphertexts
- **Decryption**: Threshold decryption by validator committee

6.2 Supported Operations

Operation	Gas Cost	Latency
Addition	50k	0.1ms
Multiplication	250k	2ms
Comparison ($<, >$)	180k	1.5ms
AND/OR/XOR	40k	0.08ms

Table 3: FHE operation costs and performance

Example Use Cases:

- Encrypted auctions (bids hidden until reveal)
- Private voting (encrypted vote tallying)
- Confidential credit scores (encrypted FICO-like computation)

7 Trusted Execution Environments (TEE)

7.1 Tier 3 Privacy Model

For regulated use cases, Z-Chain supports **TEE-based privacy**:

- Validators run Intel SGX or AMD SEV enclaves
- Smart contracts execute inside secure enclave
- Auditors receive encrypted attestations from TEE
- Regulators access transaction data via auditor keys

7.2 Attestation Protocol

Algorithm 2 TEE Transaction Attestation

Input: Transaction T, auditor public key pk_{aud}
Output: Encrypted attestation E, TEE quote Q

// Execute transaction in enclave
result $\leftarrow$ ExecuteInEnclave(T)

// Generate attestation
$A \leftarrow \{\text{sender}, \text{recipient}, \text{amount}, \text{timestamp}\}$
$E \leftarrow \text{Encrypt}(A, pk_{\text{aud}})$ ▷ Auditor can decrypt

// Remote attestation quote
$Q \leftarrow$ GenerateQuote(enclave_measurement)
return (E, Q)

Compliance Guarantee: Regulators verify TEE quote Q proves correct enclave execution, then decrypt E to audit transaction.

8 Selective Disclosure

8.1 Auditor Key System

Z-Chain implements **hierarchical auditor keys**:

1. **User Keys**: Can view own transaction history
2. **Contract Auditor Keys**: Can view all contract transactions
3. **Regulatory Keys**: Can view transactions matching specific criteria (e.g., > $10k transfers)
4. **Court Order Keys**: Can view specific addresses (requires on-chain governance vote)

8.2 View Key Protocol

Generating View Key:

$$vk = \text{HKDF}(sk_{\text{user}}, \text{“view\_key”}, \text{salt}) \tag{3}$$

Decrypting Commitment:

$$\text{PlaintextData} = \text{Decrypt}(C, vk) \tag{4}$$

Auditors receive vk (not sk_{user}), enabling read-only access without spending authority.

9 Security Analysis

9.1 Privacy Guarantees

Theorem 1 (Transaction Privacy)**.** *Under the DDH assumption and random oracle model, an adversary viewing only $L1$ commitments cannot distinguish between two transactions with different amounts/recipients with advantage greater than* $negl(\lambda)$.

Proof Sketch: Commitments are computationally hiding under DDH. zkSNARK zero-knowledge property ensures proofs leak no information beyond validity. □

9.2 Anonymity Set Size

Shielded Pool Size (as of Q4 2024):

- Total commitments: 1.2M
- Daily active commitments: 15k
- Effective anonymity set: $\approx 10^5$ per transaction

Compared to:

- Zcash shielded pool: 2.8M (but only 15% adoption)
- Monero ring size: 16 (small anonymity set)
- Tornado Cash: 50k (pre-sanctions)

10 Performance Evaluation

10.1 Throughput Benchmarks

Transaction Type	TPS	Finality	Cost
Public (Tier 0)	5,000	1.5s	$0.001
Shielded (Tier 1)	120	1.8s	$0.08
FHE (Tier 2)	50	2.2s	$0.15
TEE (Tier 3)	200	1.6s	$0.02

Table 4: Z-Chain throughput by privacy tier

10.2 Proof Generation Latency

11 Regulatory Compliance

11.1 AML/KYC Integration

Z-Chain supports **compliance without compromising user privacy**:

1. User completes KYC with licensed provider (off-chain)

Circuit	Constraints	Prove Time	Proof Size
Transfer	280k	1.2s	288 bytes
Swap	850k	3.5s	288 bytes
NFT mint	420k	1.8s	288 bytes
Loan borrow	1.2M	5.1s	288 bytes

Table 5: zk-SNARK proof generation performance

2. Provider issues **compliance certificate** (zk-attestation)
3. User submits certificate with shielded transaction
4. Smart contract verifies certificate without learning user identity

Certificate Proof:

$$\pi_{\text{kyc}} \leftarrow \text{Prove}\left(\text{HasValidCertificate}(pk_{\text{user}}, \text{provider}_{\text{id}})\right) \tag{5}$$

11.2 OFAC Compliance

To prevent sanctioned addresses, Z-Chain implements **nullifier blacklist**:

- Regulators submit sanctioned nullifiers to on-chain registry
- Smart contracts reject transactions with blacklisted nullifiers
- Privacy preserved: Only nullifier visible, not user identity

Key Advantage: Compliance without address-level deanonymization.

12 Deployment

12.1 Testnet Metrics

Z-Chain Testnet (Q3-Q4 2024):

- Transactions processed: 1.2M
- Unique addresses: 45k
- Shielded pool TVL: $18M (testnet tokens)
- Average finality: 1.85s
- Privacy breaches: 0

Phase	Timeline
Testnet v1 (zk-SNARKs only)	Q3 2024 ✓
Testnet v2 (+ FHE)	Q4 2024 ✓
Audit (Trail of Bits + OpenZeppelin)	Q1 2025 (in audit)
Mainnet launch (Tier 0-1)	Q2 2025 (in progress)
FHE mainnet (Tier 2)	Q3 2025 (in progress)
TEE mainnet (Tier 3)	Q4 2025 (in progress)

Table 6: Z-Chain deployment roadmap

12.2 Mainnet Roadmap

13 Future Work

13.1 Post-Quantum zk-SNARKs

Transitioning to quantum-resistant proof systems:

- zk-STARKs (no trusted setup, but 100× larger proofs)
- Lattice-based zkSNARKs (research phase)
- Hybrid SNARKs + STARKs (practical quantum resistance)

13.2 Cross-Chain Privacy

Enabling private transfers across chains:

- Shielded bridge with Lux L1/L2
- IBC privacy module for Cosmos
- Private cross-rollup communication

14 Conclusion

Lux Z-Chain provides **programmable privacy** for smart contracts via zk-SNARKs, FHE, and TEEs. With **120 TPS for shielded transactions** and **¡ 2s finality**, Z-Chain enables privacy-preserving DeFi with regulatory compliance. Testnet deployment with **1.2M transactions and zero breaches** demonstrates the viability of practical blockchain privacy.

A Cryptographic Primitives

A.1 zk-SNARK Parameters

Groth16 Setup:

- Trusted setup ceremony: 256 participants
- Powers of tau: 2^{22} (4.2M constraints)

- Proving key: 1.8 GB
- Verification key: 3.2 KB

A.2 FHE Parameters

TFHE Configuration:

- Security level: 128-bit (post-quantum)
- Ciphertext size: 8 KB per encrypted integer
- Bootstrap time: 15ms
- Threshold: $t = 2/3$ of validators required for decryption

B Solidity Interfaces

```
interface IZChainPrivacy {
  // Deposit into shielded pool
  function deposit(uint256 amount, bytes32 commitment)
    external returns (bool);

  // Shielded transfer (requires zk-SNARK proof)
  function transfer(bytes32 nullifier, bytes32 newCommitment,
    bytes calldata zkProof) external returns (bool);

  // Withdraw from shielded pool
  function withdraw(uint256 amount, bytes calldata zkProof,
    address recipient) external returns (bool);
}
```

Disclaimer. This document describes a testnet protocol. Mainnet security guarantees depend on successful audits and cryptographic assumptions.