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Bridging Private & Public Blockchains: A zk-SNARK Framework for Secure ERC-1155 Transfers

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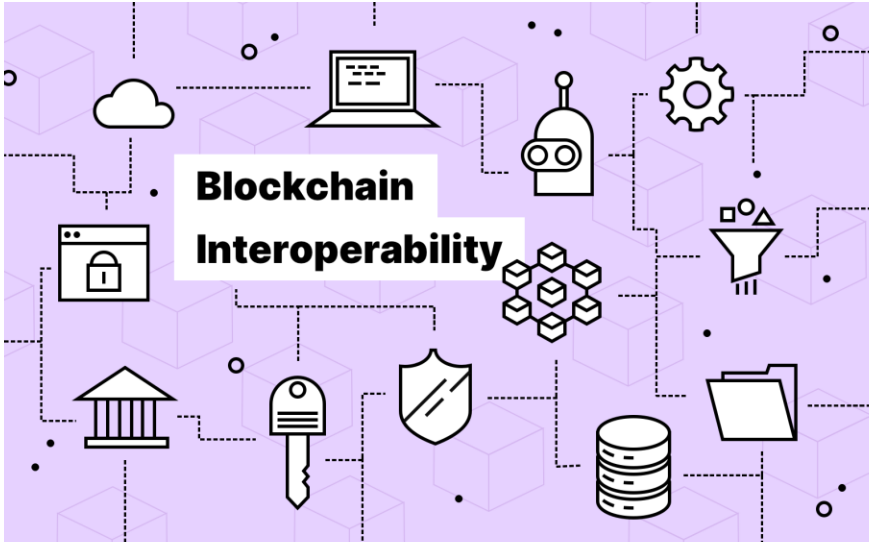
Context

Motivation

Blockchain ecosystem remains highly fragmented

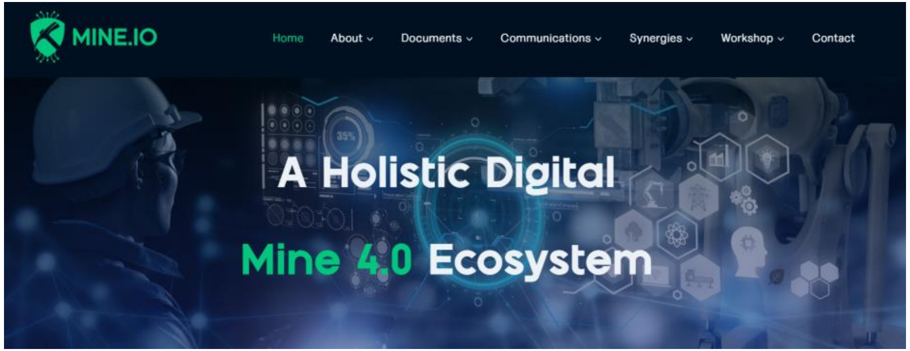
- Public and private blockchains operate in silos.
- Enterprises need secure, private asset transfer.
  - Current focus on public-to-public interoperability.
  - Some approaches for private-to-private interoperability (Hyperledger Cactus).
  - Lack of standards for private-to-public interoperability



Context

MINE.IO: Blockchain based traceability platform

- Mining waste management.
- ERC-1155 standard: fungible and non-fungible tokens.
- Hyperledger Besu: private deployment.
- It should be publicly extended to make circular economy a reality as well as to unlock monetization opportunities.
    - Interoperability with a public blockchain is recommended



https://mineio-horizon.eu/

Objective

Propose a hybrid interoperability solution in cross-chain private-to-public transactions

- Hashed Timelock Contracts (HTLCs) based locking.
- Zero knowledge Proofs (ZKPs)
- Relayer-assisted proof coordination

- Allow interoperability of MINE.IO solution (Hyperledger Besu) with public Ethereum compatible networks.

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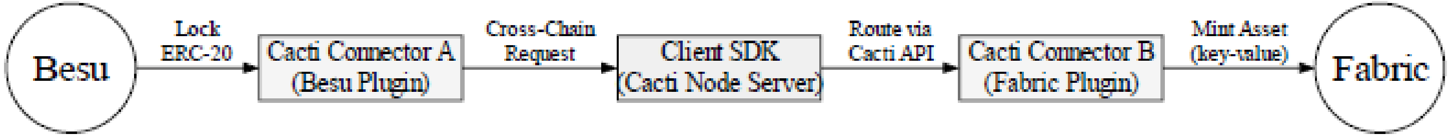
State of the Art

Current Interoperability Solutions

Hyperledger Cacti for private-to-private interoperability


Besu
Lock ERC-20
Cacti Connector A (Besu Plugin)
Cross-Chain Request
Client SDK (Cacti Node Server)
Route via Cacti API
Cacti Connector B (Fabric Plugin)
Mint Asset (key-value)
Fabric

Key cross-chain mechanisms

- A **bridge** relies on a verifier to validate messages from a smart contract on Blockchain A (origin) and relay them to Blockchain B (target).
- **Atomic swaps** allow direct peer-to-peer exchanges of tokens across blockchains without trust in intermediaries.
- **HTLCs** (Hashed Timelock Contracts) enforce conditional transactions using cryptographic hash functions. Funds remain locked until all participants meet the predefined conditions.
- **Relay chains** act as intermediaries, monitoring multiple blockchains and validating cross-chain transactions.
- **Sidechains** are independent blockchains connected to a primary blockchain. They allow asset transfers between chains while reducing congestion on the main network.

Key cross-chain mechanisms

- A **bridge** relies on a verifier to validate messages from a smart contract on Blockchain A (origin) and relay them to Blockchain B (target). → **Third parties are involved.**
- **Atomic swaps** allow direct peer-to-peer exchanges of tokens across blockchains without trust in intermediaries. → **Simple but with limited flexibility.**
- **HTLCs** (Hashed Timelock Contracts) enforce conditional transactions using cryptographic hash functions. Funds remain locked until all participants meet the predefined conditions → **trustless and lightweight solution**
- **Relay chains** act as intermediaries, monitoring multiple blockchains and validating cross-chain transactions. → **Third parties are involved.**
- **Sidechains** are independent blockchains connected to a primary blockchain. They allow asset transfers between chains while reducing congestion on the main network. → **Complex infrastructure**

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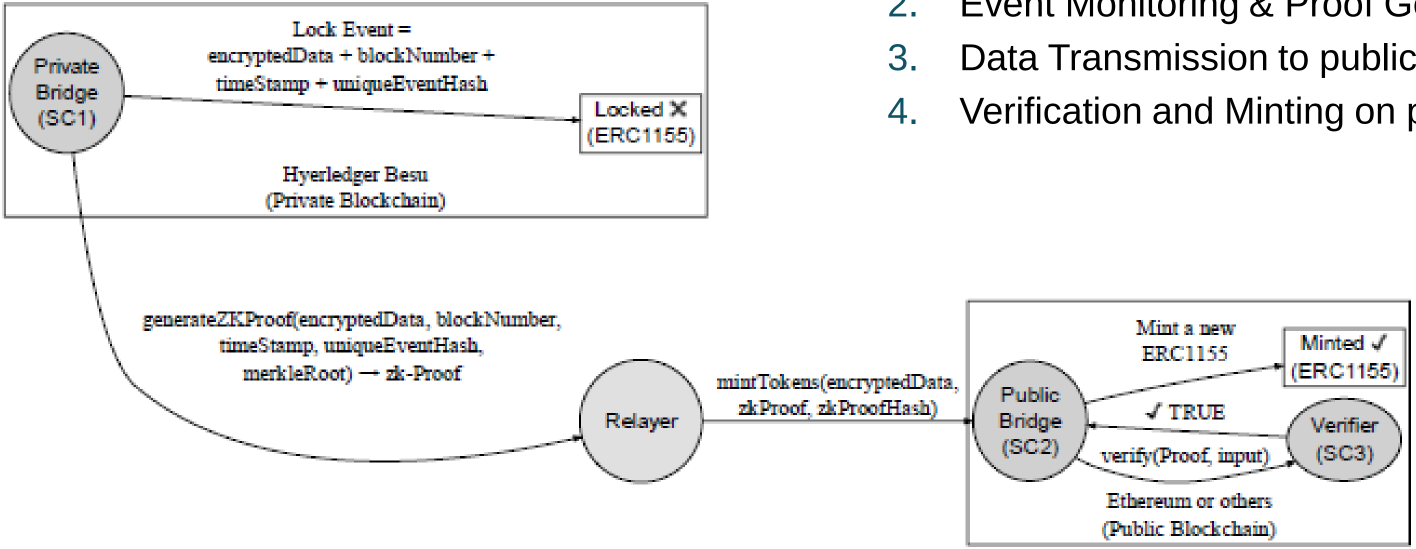
Proposal

Architecture and Workflow



Private Bridge (SC1)
Lock Event = encryptedData + blockNumber + timeStamp + uniqueEventHash
Locked ✗ (ERC1155)
Hyerledger Besu (Private Blockchain)
generateZKProof(encryptedData, blockNumber, timeStamp, uniqueEventHash, merkleRoot) → zk-Proof
Relayer
mintTokens(encryptedData, zkProof, zkProofHash)
Public Bridge (SC2)
Mint a new ERC1155
Minted ✓ (ERC1155)
✓ TRUE
verify(Proof, input)
Verifier (SC3)
Ethereum or others (Public Blockchain)

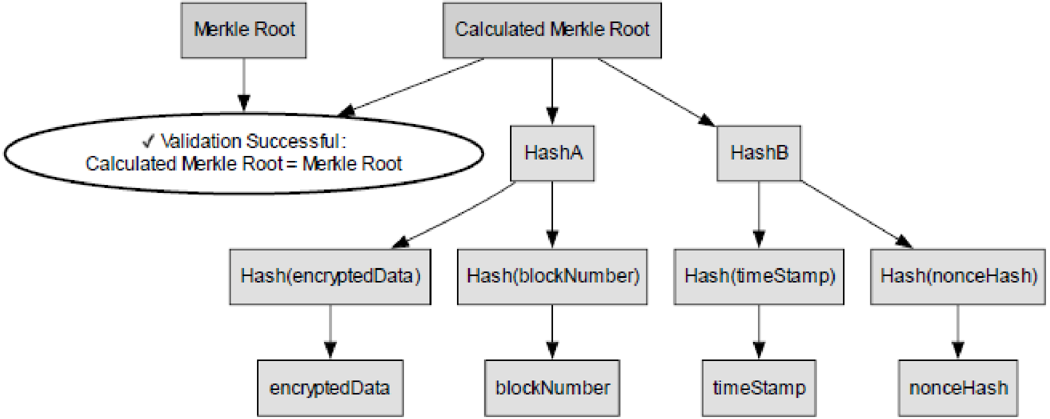
1. Locking on Besu.
2. Event Monitoring & Proof Generation
3. Data Transmission to public network
4. Verification and Minting on public network

Security by ZoKrates: verifier

It validates that the data received by the relayer in the locked event → If positive, the token is minted.

It generates the merkle root without publicly exposing these sensitive values.

It automatically generates the verifier smart contract with the described logic.



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Results

Validation: MINE.IO

Trace mining waste assets inside a pyrometallurgical process

Novel **circular economy** approaches as well as the current **strict regulations** on the management of mining waste in the European Union highlight the need for the tokens representing waste assets (i.e., tailings, slag, etc.) to be managed in public networks where **transparency is greater**.

New value strings in **DeFi ecosystems**.

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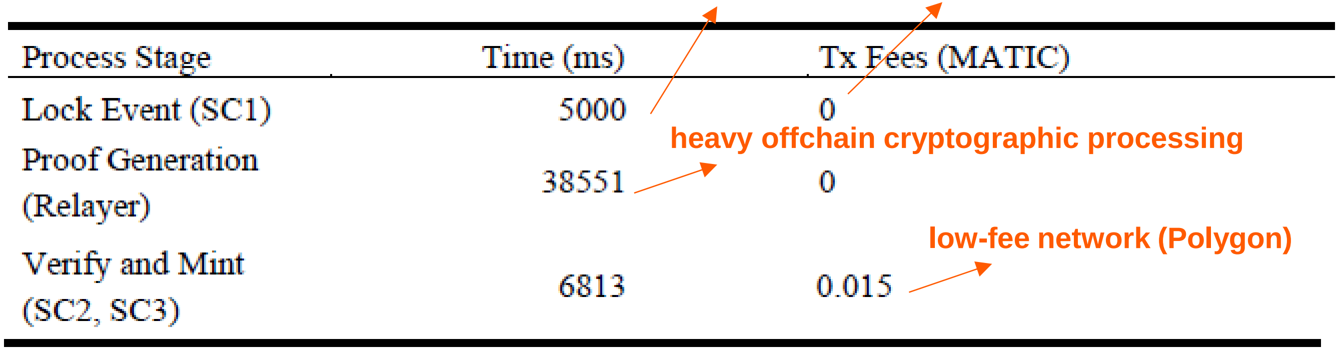
Validation: MINE.IO

Considered technologies: Besu, Amoy (Polygon testnet), hardhat, Node.js Relayer, ZoKrates.



Process Stage	Time (ms)	Tx Fees (MATIC)
Lock Event (SC1)	5000	0
Proof Generation (Relayer)	38551	0
Verify and Mint (SC2, SC3)	6813	0.015

Block time

Zero Base Fee

heavy offchain cryptographic processing

low-fee network (Polygon)

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Conclusions

Conclusions & Future Work

Secure and scalable token migration between private (Hyperledger Besu) and public (Amoy) blockchain networks

- Secure ERC-1155 bridging is feasible
    - Public/private bridges enable transparency & value.
    - zkSNARKs bring privacy to interoperability

- Domain agnostic
    - Applied to MINE.IO traceability solution

- **Future work:**
    - Explore zkSNARK batching for higher efficiency
    - Analyze more complex ZKP solutions.(e.g., Circom).
    - Extend comparative studies with other alternatives.

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