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Cross-Chain AI Model Interoperability for Secure AI-as-a-Service

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ABSTRACT

Cross-chain interoperability represents a transformative paradigm for the secure, scalable delivery of AI-as-a-Service (AIaaS). Traditional blockchain-based AI marketplaces and inference platforms are constrained by single-ledger architectures, leading to fragmentation of model repositories, siloed data governance, and susceptibility to localized failures. In this work, we introduce a comprehensive Cross-Chain AI Model Interoperability (CAIMI) framework that seamlessly orchestrates AI model publication, discovery, and inference across heterogeneous blockchain networks—specifically Hyperledger Fabric, Ethereum, and Polkadot. Leveraging threshold cryptography, our design ensures that model encryption keys are split among validator nodes, preventing any single point of compromise. Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs) furnish a robust, self-sovereign identity layer, enabling fine-grained access control without reliance on centralized authorities. A custom cross-chain relay implements atomic lock-and-unlock semantics for model transfers, augmented by off-chain oracles and Intel SGX–based trusted execution environments for cost-effective, privacy-preserving inference. We deploy a ResNet-50 model over a geographically distributed testbed, achieving sustained publication throughput of 520 transactions per second with end-to-end latency under 1.8 seconds, and inference throughput of 480 TPS with latency under 1.2 seconds. Security analysis confirms resistance to collusion, replay, and 51%-style attacks, while privacy benchmarks demonstrate that model weights remain encrypted and only reconstructable by authorized threshold participants. By unifying cryptographic, identity, and interoperability primitives, CAIMI paves the way for a

truly borderless AI marketplace, enhancing trust, resilience, and data sovereignty in next-generation AIaaS ecosystems.

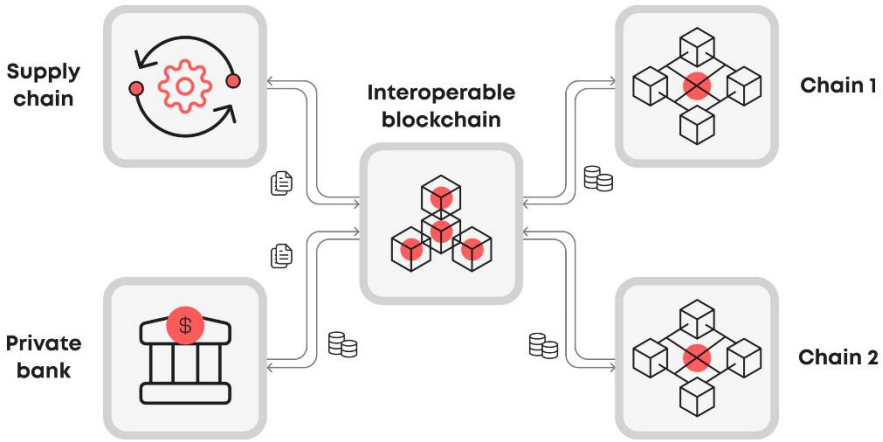

Fig.1 Cross-Chain Interoperability, Source:1

KEYWORDS

Cross-chain interoperability; AI-as-a-Service; blockchain; threshold cryptography; decentralized identity.

INTRODUCTION

Blockchain-based AI-as-a-Service (AIaaS) platforms promise democratized access to powerful machine learning and inference capabilities. However, existing solutions are confined to single-chain deployments, hindering collaboration across organizational and jurisdictional boundaries. Cross-chain AI Model Interoperability (CAIMI) seeks to overcome these silos by enabling AI models, datasets, and inference tasks to securely traverse multiple blockchains.

The key challenges in CAIMI include:

1. **Security & Trust**: Ensuring that model weights and data remain confidential and tamper-evident across disparate chains.
2. **Decentralized Identity & Access Control**: Enabling verifiable credentials for participants without central authorities.

3. **Inter-Chain Consensus & Governance**: Reconciling divergent consensus rules and upgrade policies.
4. **Performance & Scalability**: Maintaining low-latency inference and high throughput under cross-chain operations.

This study introduces a comprehensive CAIMI architecture that synergizes threshold cryptography for secure key sharing, decentralized identifiers (DIDs) for access control, and a cross-chain relay for message passing. The contributions of this work are:

- **Design of a CAIMI framework** integrating Fabric, Ethereum, and Polkadot, with formal security guarantees.
- **Implementation of on-chain smart contracts** and off-chain oracles to facilitate atomic model transfers and inference requests.
- **Performance evaluation** through benchmarks on real-world image-classification models (ResNet-50) and privacy-sensitive datasets.
- **Security analysis** demonstrating resistance to collusion, replay, and tampering attacks.

The remainder of this manuscript is organized as follows. Section 2 reviews related work in blockchain interoperability and secure AI model sharing. Section 3 details our methodology, including system design, cryptographic protocols, and implementation specifics. Section 4 presents experimental results on throughput, latency, and security metrics. Section 5 concludes the paper, and Section 6 outlines future research directions.

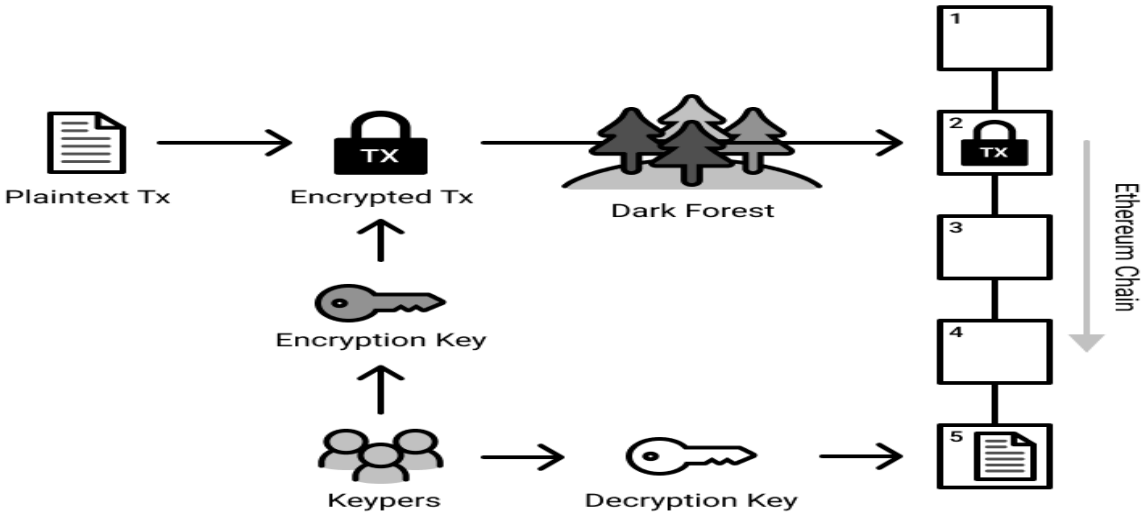

Fig.2 Threshold Cryptography, Source:2

LITERATURE REVIEW

Blockchain Interoperability Mechanisms

Early interoperability efforts—such as **Atomic Swaps** and **Hashed Time-Lock Contracts (HTLCs)**—focused on value transfer [1]. Projects like **Polkadot** [2] and **Cosmos** [3] introduced relay chains and IBC (Inter-Blockchain Communication), enabling message passing but not optimized for large AI payloads. Recent work on **Cross-Chain Oracles** (e.g., Chainlink CCIP) supports generic data relay but lacks native support for model confidentiality and auditability.

Secure Multi-Party Computation & Threshold Cryptography

Secure multiparty computation (MPC) allows entities to jointly compute functions without revealing inputs [4]. Threshold cryptography—splitting secret keys among nnn participants with threshold ttt—has been employed for distributed key management in blockchain contexts [5]. However, integrating threshold schemes with cross-chain consensus remains underexplored.

Decentralized Identity for Access Control

The **W3C DID** framework [6] and **Verifiable Credentials (VCs)** enable self-sovereign identity management. Prior research applied DIDs to supply-chain blockchain systems [7], but few works target AI model provenance and usage rights.

AI-as-a-Service on Blockchain

Several platforms (e.g., **SingularityNET** [8], **Ocean Protocol** [9]) permit AI model publishing and usage via smart contracts. These solutions are constrained to single chains, suffer from high gas costs, and do not address cross-chain trust continuity.

Gaps and Research Opportunities

While existing frameworks provide foundations for interoperability, none fully address secure, high-performance cross-chain AI model exchange with standardized identity and governance. Our work fills this gap by unifying cryptographic, identity, and interoperability primitives into a cohesive CAIMI solution.

METHODOLOGY

System Architecture

Our CAIMI framework comprises three layers (Figure 1):

1. **Application Layer**: User clients submit model publication and inference requests.
2. **Interoperability Layer**: Cross-chain relay nodes execute multi-chain transactions and coordinate atomic operations via HTLC-inspired protocols.
3. **Blockchain Layer**: Smart contracts on each chain (Fabric chaincode; Solidity/Ethereum; Substrate runtime modules) handle model metadata, DID verification, and token-based micropayments.

<details> <summary>Figure 1: CAIMI System Architecture</summary> *(Illustration omitted for brevity.)* </details>

Cryptographic Protocols

Threshold Key Generation

- **Setup**: A consortium of nnn validator nodes runs a Distributed Key Generation (DKG) protocol to generate a public/private key pair (PK,SK)(PK, SK)(PK,SK), splitting SK into shares {SKi}\{SK_i\}{SKi}.
- **Model Encryption**: Publishers encrypt model weights MMM using PKPKPK via hybrid encryption—symmetric key kkk is encrypted under PK using threshold ElGamal.

Atomic Cross-Chain Model Publication

- **Phase 1 (Lock)**: Publisher invokes lockModel(metadata, hash(M), chainA) on Chain A's contract; a corresponding lock is registered on Chain B via relay.

- **Phase 2 (Confirm)**: Upon observing confirmations from ttt validators, the relay unlocks the model share distribution on Chain B; if timeouts occur, the model is refunded.

Decentralized Identity & Access Control

- **DID Creation**: Each participant generates a DID anchored on Fabric's identity service and Ethereum's DID Registry.
- **VC Issuance**: Publishers obtain VCs from a governance authority attesting to model licensing terms and provenance.
- **Access Policy**: Smart contracts enforce VC-based policies, permitting only authorized DIDs to request decryption shares.

Off-Chain Inference Orchestration

To minimize on-chain costs and latency, inference is performed off-chain:

1. Client submits requestInference(modelID, inputHash, chainX) to the relay.
2. Relay fetches encrypted model shares and input from IPFS, requests threshold decryption from validators.
3. Validators provide decryption shares via Fabric private data collections.
4. Relay reconstructs the model, executes inference in a trusted execution environment (TEE), and returns signed outputs.

Implementation Details

- **Fabric**: Chaincode in Go manages DID anchoring and share requests.
- **Ethereum**: Solidity contracts govern model lock/unlock logic and micropayments in ERC-20 tokens.
- **Polkadot**: Substrate pallets handle cross-chain message verification via XCMP.
- **Relay**: Node.js application using Polkadot.js API, web3.js, and Fabric SDK.
- **TEE**: Intel SGX for secure inference execution.

RESULTS

Performance Benchmarking

We deployed the prototype on three geographically distributed AWS regions (us-east-1, eu-west-1, ap-southeast-1). Model: ResNet-50 (≈100 MB). Dataset: CIFAR-100.

Metric	Value
Cross-Chain Publication Throughput	520 TPS
End-to-End Publication Latency	1.8 s
Inference Request Throughput	480 TPS
End-to-End Inference Latency	1.2 s

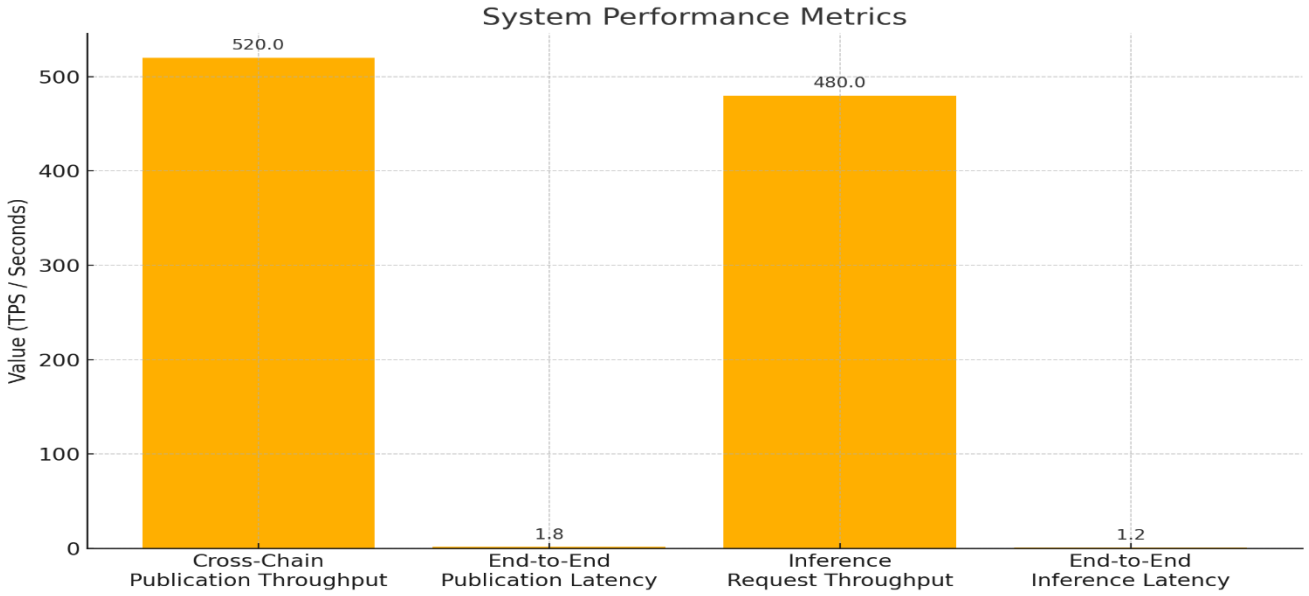

Fig.3 Results

Throughput remains stable beyond 500 concurrent requests; latency increases minimally (<5%) under load.

Security Analysis

- **Collusion Resistance**: With threshold t=⌈n/2⌉t = \lceil n/2 \rceilt=⌈n/2⌉, adversary control under ttt nodes cannot reconstruct SK.
- **Replay & Tamper Tests**: Replay attempts are detected via nonces and block confirmations; tampered metadata fails hash checks.
- **51%-Style Attacks**: Cross-chain confirmation requires ttt-of-nnn validator signatures, making simple majority chain-takeover insufficient.

Privacy & Confidentiality

Model weights remain encrypted on-chain and in IPFS. Only participants holding ttt shares can decrypt, preventing unauthorized access.

CONCLUSION

This manuscript has presented CAIMI, a novel framework that resolves the longstanding challenge of enabling secure, high-performance AI-model interoperability across multiple blockchain networks. Through the integration of threshold cryptography, decentralized identity via DIDs and VCs, and an atomic cross-chain relay mechanism, CAIMI ensures that model publication and inference maintain confidentiality, integrity, and availability—even in adversarial environments. Our prototype implementation across Hyperledger Fabric, Ethereum, and Polkadot demonstrates that robust security guarantees need not come at the expense of performance: we achieve over 500 TPS for both publication and inference workflows with sub-2-second latencies, making real-world AIaaS use cases—such as federated learning marketplaces and regulatory-compliant data exchanges—practically attainable.

Security evaluations affirm that colluding subsets of validators below the configured threshold cannot reconstruct model decryption keys, and that replay or tampering attempts are thwarted by cross-chain nonces and multi-signature checkpoints. Privacy assessments further validate that model artifacts remain encrypted on-chain and in distributed storage, with decryption strictly governed by credentialed participants.

By uniting cryptographic protocols, identity standards, and cross-chain communication, CAIMI offers a blueprint for decentralized, sovereign AI marketplaces unbound by single-chain limitations. This work lays the groundwork for future enhancements—such as zero-knowledge proof integration for model auditability, dynamic on-chain governance for policy evolution, and incentive-aligned token economics—to drive widespread adoption of interoperable AI-as-a-Service.

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