# EquiLink Bridge: A Semi-Custodial Approach to Cross-Chain Transactions via TEE

Tingda Shen, Yebo Feng, Jin Dong, Konglin Zhu, Lei Jiao, and Lin Zhang

***Abstract*—The rising demand for blockchain interoperability is accelerating advancements in cross-chain bridge technologies, which are crucial for a seamless information transfer in multi-blockchain ecosystems. Existing blockchain bridges are typically classified into two categories: custodial and non-custodial. Custodial bridges use a trusted third party for easier and faster transactions but depend on custodian trust, while non-custodial bridges enhance transparency and control with smart contracts but increased complexity and latency. Currently, no bridge design successfully combines the benefits of both while avoiding their drawbacks. This paper presents EquiLink, a semi-custodial bridge that combines the benefits of both custodial and non-custodial methods. EquiLink employs a smart contract, known as the EquiLink Service, to initiate cross-chain transfers. It then uses the EquiLink Network, a system composed of remote-attested Trusted Execution Environments (TEEs), to verify and issue these transfers between two blockchains. Any eligible participants validated through remote attestation can join the EquiLink Network and contribute to the bridge's functionality. Additionally, participants are regulated by an economic model, providing an extra layer of security through economic incentives. This semi-custodial bridge enhances transparency and control for users. Meanwhile, it mitigates the risks associated with centralized custody and decentralization. In the evaluation, EquiLink is resilient against both replay and physical attacks. Additionally, it operates efficiently, reducing transaction costs by 14.1% and latency by 18.9%.**

***Index Terms*—blockchain, cross-chain bridge, hash time-lock contract, semi-custodial model, trusted execution environment.**

## I. Introduction

As blockchain ecosystems undergo rapid growth, CoinGecko data indicates that 242 blockchain networks surpassed $86.9 billion in Total Value Locked (TVL) by April 2025 [1]. This expansion has led to the emergence of heterogeneous blockchain platforms with distinct characteristics and functionalities, forming a multi-chain ecosystem [2]. Consequently, the need for interoperability and seamless value transfer has become increasingly critical, making cross-chain bridges more crucial than ever [3]. Cross-chain bridges establish connections between independent blockchains, enabling decentralized applications (dApps) to operate across heterogeneous networks by facilitating both asset and data transfers [4], [5]. As a fundamental technology for blockchain interoperability, cross-chain bridges serve as the backbone of the multi-chain ecosystem, driving the global digital economy.

Cross-chain bridges are typically classified into custodial and non-custodial types [6]. Custodial bridges rely on a trusted third party to manage user assets and facilitate transfers, which usually improves efficiency and simplifies transaction coordination, but also introduces dependence on the custodian and potential single points of failure [7]. In contrast, non-custodial bridges eliminate trusted intermediaries and instead rely on consensus protocols, smart contracts, and cryptographic techniques to enable trustless cross-chain transactions [7]. While such designs improve transparency and user control, their reliance on decentralized verification and coordination often increases system complexity and reduces transfer efficiency [3].

The two prevailing types of cross-chain bridges exhibit inherent limitations. Custodial bridges prioritize easier and faster transactions, yet they suffer from inherent transparency limitations in asset custody and remain exposed to single points of failure, while non-custodial bridges offer enhanced transparency and user control [6], [8], [9], yet they often suffer from increased system complexity and reduced efficiency. Current solutions generally favor different trade-offs, making it difficult to design a bridge that simultaneously meets the requirements of efficiency, decentralization, and security. To address this challenge, semi-custodial bridges have emerged as a promising architectural paradigm that combines on-chain asset custody with trusted off-chain execution or verification components. In such designs, assets remain locked in smart contracts on the blockchain, while certain coordination or verification tasks are delegated to trusted entities or specialized execution environments. This hybrid trust model enables semi-custodial bridges to balance the trade-offs between efficiency, security, and decentralization.

This paper aims to balance efficiency, decentralization, and security by proposing a novel semi-custodial cross-chain bridge scheme called the EquiLink Bridge. EquiLink leverages trusted hardware to secure off-chain execution, thereby reducing the high cost of on-chain operations. Concretely, EquiLink combines lightweight on-chain verification with decentralized governance of public participants equipped with Trusted Execution Environments (TEEs) to enhance both efficiency and

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decentralization. TEEs are isolated environments designed to ensure the confidentiality and integrity of workloads [10]. When combined with blockchains, TEEs enable efficient and confidential off-chain computation while the blockchain maintains consensus and verifiable state on-chain. Public participants equipped with TEEs can undergo remote attestation to join the network as *trusted participants*, who form the core of EquiLink's decentralized verification network. This network is responsible for securely executing and validating cross-chain transactions within their respective TEEs.

Specifically, EquiLink includes three main components: (i) the EquiLink Service $ES$, (ii) the Light Server $LS$, and (iii) the EquiLink Network $EN$. The $ES$, composed of smart contracts and InterPlanetary File System (IPFS), provides decentralized functionality for node routing, fund staking, and code distribution, enabling governance over cross-chain transactions and participants. The $LS$ is responsible for authenticating TEE-based participants via remote attestation to establish a root of trust, enabling public participants to join the EquiLink Network. The $EN$, composed of trusted participants, forms a decentralized verification network in which participants may serve as validators for transaction verification or as watchtowers for detecting and penalizing misbehavior, thereby enabling non-custodial cross-chain transactions. For each transaction, a subset of trusted participants is randomly selected from the network to execute and verify the cross-chain operation. By combining hardware-backed trust with decentralized coordination, EquiLink realizes a semi-custodial cross-chain bridge.

Experimental evaluations illustrate that the proposed solution significantly improves transaction costs, transaction latency, and overall resource consumption, and confirms the effectiveness of its economic model and attack resistance. EquiLink reduces average transaction costs by 14.1%, achieving 289k gas (optimistic) and 302k gas (pessimistic), while decreasing transaction latency by 18.9% on average and 70% in high-congestion scenarios. The system's overall overhead illustrates that the entry and exit costs for participants in EquiLink can be amortized after validating only a small number of transactions. Furthermore, off-chain validation of 1,000 transactions is completed within 55 seconds on a 4-core, 16 GB machine, indicating that EquiLink imposes low hardware requirements and reduces the entry barriers for participants. In addition, a game-theoretic analysis confirms that the economic model can reach a stable equilibrium. Finally, we reproduced replay and physical attacks to verify the system's strong resilience against adversarial behaviors.

The primary contributions of this paper are as follows.

- **Semi-Custodial Bridge Solution:**
  We propose a semi-custodial cross-chain bridge that leverages a TEE-enabled validator network to support cost-efficient transfers across heterogeneous blockchains. By combining the strengths of custodial and non-custodial designs, the bridge reduces costs and latency through off-chain trusted execution, preserves transparency via decentralized services, and enhances security through a dual-hash locking mechanism coordinated by TEEs and watchtowers.
- **Efficient and Reliable Interoperability:**
  We design a decentralized EquiLink Network that distributes validation and monitoring across publicly accessible trusted participants, eliminating single points of failure and maintaining robustness under failures or adversarial conditions. A tailored protocol shifts resource-intensive verification to secure off-chain execution, thereby improving both efficiency and reliability of interoperability.
- **Sustainable Economic Model:**
  The system ensures sustainability through three mechanisms: *monetary incentives* rewarding validators via gas fees, *staking* penalizing misbehavior through stake confiscation, and a *watchtower mechanism* providing secondary verification, timeout recovery, and compensation.
- **Code release:** The code is openly available at [https://github.com/Stdwill/EquiLink-bridge], providing transparency and enabling further development and collaboration.

## II. Related Work

This section introduces TEE-blockchain systems, classifies cross-chain mechanisms, reviews representative cross-chain bridge designs, and discusses the inherent limitations of both custodial and non-custodial approaches.

### A. TEE-blockchain Systems

TEE-blockchain systems refer to hybrid architectures that integrate blockchains with trusted execution environments, where blockchains provide consensus and persistent state while TEEs execute computations over private data off-chain. This design leverages the complementary properties of both technologies, enabling confidential and efficient execution while maintaining verifiable state on-chain. Ekiden [11] is the first system to propose a hybridized TEE-blockchain architecture, where computation is separated from consensus for smart contract execution. However, contracts in Ekiden are largely isolated and lack strong interoperability capabilities. Phala Network [12] extends this idea by building a distributed confidential computing network based on TEE workers to support cross-contract and cross-chain interactions. Liu et al. [8] propose a TEE-enabled framework that leverages trusted sensors and consistency protocols to securely upload off-chain data to the blockchain.

Although TEE–blockchain systems can combine the advantages of both technologies, such hybrid architectures may also introduce new security challenges compared with single-architecture designs. For instance, the execution of TEEs still relies on the underlying host system, and a malicious host may manipulate scheduling or even induce physical faults [10], potentially interrupting execution or causing inconsistent states. Moreover, the lack of a reliable trusted timer within TEEs makes it difficult to determine the freshness of blockchain states [11], thereby introducing additional challenges for state synchronization and secure verification.

### B. Custodial Bridges

Custodial bridges rely on a trusted authority to facilitate asset transfers across blockchain networks. In such

systems, users must trust a centralized operator to lock, mint, and distribute assets during the cross-chain transfer process [13]. Representative centralized bridges include cBridge [14], Across Protocol [15], Rhino.fi [16], Multichain [17], Binance Bridge [18], and Polybridge [19]. For example, Binance Bridge supports transfers between Binance and Ethereum by leveraging Binance's infrastructure to manage the process. Similarly, Rhino.fi stores assets on different chains under the control of a central operator, enabling users to transfer assets by interacting with the operator's account during cross-chain transactions [20]. The xDAI Bridge [21] employs a lock-and-mint mechanism, using smart contracts to facilitate transfers from Ethereum to the Gnosis chain. In this system, assets are held by TokenBridgeDAO members, while xDAI tokens are minted and distributed through a multisignature approval scheme.

While custodial bridges offer higher efficiency and lower latency, they also entail significant risks. A major concern is the inherent single point of failure, where centralized nodes can lead to catastrophic asset loss during hacks or regulatory actions [22]. Moreover, centralized operators hold the power to approve or reject transactions at their discretion, resulting in limited transparency. For example, the disappearance of Multichain's founder caused operational paralysis, highlighting the vulnerabilities of relying on a central authority for critical infrastructure [17], [22]. Furthermore, these bridges may face stricter regulatory scrutiny due to their resemblance to traditional financial institutions [23]. In contrast, EquiLink replaces the centralized operator in custodial bridges with a decentralized validator network, thereby avoiding the single point of failure inherent in custodial designs. This decentralized architecture ensures that transaction validation is no longer controlled by a single trusted entity, improving transparency and verifiability in cross-chain operations.

### C. Non-custodial Bridges

In contrast to custodial solutions, non-custodial bridges eliminate the need for trusted intermediaries by distributing trust across multiple independent nodes. They can be classified as Multi-Party Computation (MPC), Zero-knowledge proofs (ZKPs), payment-channel-based, or liquidity-pool-based approaches. Representative decentralized bridges include Rainbow Bridge [24], zkCross [25], zkBridge [26], XClaim [27], Stargate [28], Chainlink [29], and ALBA Cross-Chain Bridge [30]. For example, Multichain (formerly AnySwap) uses an MPC-based Threshold Signature Scheme (TSS) to enable transfers within 3–30 minutes [31], while zkBridge employs ZKPs to secure transactions, generating 128 signatures in 18 seconds with sub-2-minute delays [26]. Similarly, zkCross offers a two-layer solution to address cross-chain privacy and auditing challenges [25]. Horizon adopts a gas-efficient approach for trustless transactions without compromising decentralization [32], while ALBA Cross-Chain Bridge introduces Pay2Chain bridges that leverage off-chain payment channels [30].

Despite their advantages, non-custodial bridges typically incur higher communication costs and performance overheads due to the need for consensus among multiple nodes, increasing transaction complexity and latency [33]. Studies modeling cross-chain processes, such as queueing theory applications in the Cosmos network, provide insights into the trade-offs between system throughput and latency, further illustrating the challenges in optimizing non-custodial bridge performance [34]. Additionally, the complexity of non-custodial bridges also makes them more susceptible to vulnerabilities [6]. Several bridge-related exploits have been attributed to issues such as poor private key management and flaws in smart contract logic [6]. In contrast, EquiLink establishes trust for newly joined public participants through remote attestation and leverages TEE-based trusted participants during transaction validation. By doing so, it reduces reliance on gas-intensive on-chain consensus and verification. In this sense, EquiLink introduces TEEs into cross-chain verification as a design choice well suited to the verification bottleneck, thereby reducing on-chain overhead and improving efficiency and latency compared with existing approaches.

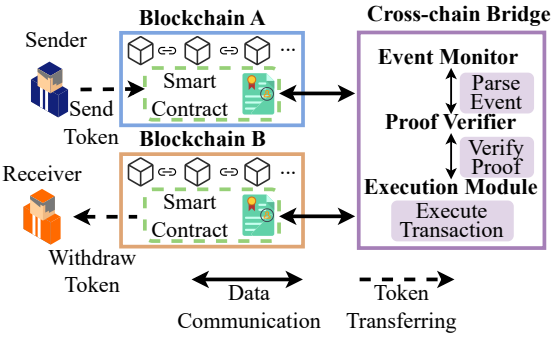


Fig. 1 The system framework of EquiLink.

## III. System and Security Model

### A. System Model

In a cross-chain bridge system, we consider several key roles and components. Fig. 1 illustrates the framework of a general cross-chain bridge. The bridge involves a set of blockchains, denoted as $BC_s$ and $BC_r$, which are responsible for maintaining independent ledgers in cross-chain transactions. Users, acting as senders on $BC_s$ and receivers on $BC_r$, initiate cross-chain transactions. A generic cross-chain bridge must incorporate three components to enable secure and reliable cross-chain transactions: an Event Monitor, a Proof Verifier, and an Execution Module. The Event Monitor continuously observes on-chain smart contracts to capture transaction-related events. The Proof Verifier authenticates the associated data to ensure that the reported transaction has indeed occurred on the source blockchain. Upon successful verification, the Execution Module performs the corresponding cross-chain operation on the destination blockchain, thereby completing the asset transfer.

EquiLink instantiates these three components using trusted participants equipped with TEEs. These participants are assigned to two distinct roles in each cross-chain transaction: validators $v$ that capture transaction-related events and attest to the correctness of cross-chain transactions and watchtowers $wt_i$ that monitor protocol execution and detect potential misbehavior. By leveraging TEEs, these participating nodes can

provide integrity guarantees for critical operations. To enable interoperability, the system includes an on-chain coordination service with smart contracts that manages transaction requests and state synchronization between heterogeneous blockchains. Additionally, other trusted components, such as a Light Server, are leveraged to provide remote attestation to verify the correctness and trustworthiness of participants. The key notations used throughout the paper are summarized in Table III in Appendix.

### B. Threat Model

The objective of a cross-chain bridge is to correctly and securely complete each transaction from $BC_s$ to $BC_r$. We define the adversary $\mathcal{A}$ as an entity aiming to disrupt cross-chain transactions for financial gain or to degrade system availability. We assume that remote attestation is carried out by a set of trusted replicated attesters in the Light Server. A participant is admitted only when more than half of the attesters approve the attestation result, thereby proving the identity and code integrity of TEE-based participants. The EquiLink Service is assumed to provide the pre-defined cross-chain transaction services; however, it may be subject to exploitation by the adversary $\mathcal{A}$ due to potential smart contracts vulnerabilities.

We further assume that all cryptographic primitives used in the system are secure and that the underlying blockchains achieve consensus finality after transaction confirmations. We assume that the remote attestation mechanism can correctly verify the identity and integrity of honest TEEs, and that honest TEEs execute the intended code faithfully. However, we do not assume that all TEEs remain uncompromised. In practice, an adversary may compromise a subset of TEE-based participants or attempt to exploit side-channel leakage.

The adversary may include malicious senders or external attackers. Malicious senders may attempt to initiate double-spending transactions to obtain unauthorized assets. External attackers may disrupt the network or compromise a subset of TEE-based participants (including validators and watchtowers), gaining control over message delivery and potentially modifying, delaying, or dropping messages. They may also attempt to extract sensitive information through side-channel attacks, exploit vulnerabilities in smart contracts, or launch physical attacks against participating nodes. We assume that the adversary may compromise a subset of TEE-based participants but cannot compromise all TEEs involved in a given transaction simultaneously. In particular, the protocol remains secure as long as at least one participant in the decentralized verification group (DVG) executes the protocol correctly. Secure communication channels are assumed between honest participants. Based on the attacker's capabilities and goals, we consider the following attacks:

1) **Double-Spending Attacks**: A malicious sender issues two conflicting transactions $t_1, t_2$ on $BC_s$ that spend the same input/nonce, attempting to bypass asset locking and mint duplicate assets on $BC_r$, violating value conservation.
2) **Replay Attacks**: A valid transaction $t$ on $BC_s$ is intercepted and resent to $BC_r$, triggering unauthorized asset issuance and breaking transaction uniqueness.
3) **Compromised Participants**: A corrupted or malicious participant $p_{\text{mal}}$ may forge, drop, or equivocate on transactions, producing a tampered one $\tilde{t} = \mathcal{A}(t)$ or selectively relaying $t$, causing ledger divergence or false confirmations.
4) **Side-Channel Attacks**: An adversary may attempt to extract sensitive information from TEEs through side-channel attacks (e.g., cache timing or speculative execution leakage), potentially revealing secrets used in cross-chain transaction validation.
5) **Physical Faults**: Node crashes or disconnections interrupt transaction processing ($t_{\text{status}} = 1$), raising fund-recovery concerns for sender $A_s$.

### C. Design Goals

An ideal cross-chain system should satisfy the following security properties:

- *Accurate and Secure:* The system must correctly and securely process cross-chain transactions, ensuring that assets are transferred with the exact amount to the intended recipient while preventing any unauthorized manipulation. It guarantees that each transaction executes atomically—either fully succeeds or fully fails—within a bounded time frame to avoid indefinite asset locking.
- *Incentive and Penalty Mechanism:* The system should align rewards and penalties to encourage honest participants and penalize malicious ones, so that following the protocol is always the most economically rational choice.
- *Efficient:* The system should minimize transaction latency and computational overhead by using TEEs to execute cross-chain logic off-chain while requiring only lightweight on-chain verification.
- *Low Cost:* The design should reduce on-chain gas consumption by shifting expensive computation and validation tasks to TEE-based off-chain participants. By relying on TEEs to guarantee correctness without full on-chain consensus, the system significantly lowers transaction fees, making cross-chain transfers economically viable.

## IV. System Design

In this section, we present the detailed system description, including the overall architecture and the functionality of each component.

### A. Overview

EquiLink achieves efficient, secure, and decentralized cross-chain interactions through off-chain computation with on-chain lightweight verification, TEE-based trust establishment, and the inclusion of public participants.

As presented in Fig. 2, EquiLink consists of three modules: EquiLink Service ($ES$), Light Server ($LS$), and EquiLink Network ($EN$). Specifically, (i) $ES$ provides the on-chain support for cross-chain transfer through three core contracts: the router contract $C_{\text{router}}$, the staking contract $C_{\text{staking}}$, and the cross-chain transaction contract $C_{\text{tx}}$; (ii) $LS$ provides third-party support for remote attestation and maintains a trusted router list stored on $C_{\text{router}}$; and (iii) $EN$ is a set of trusted

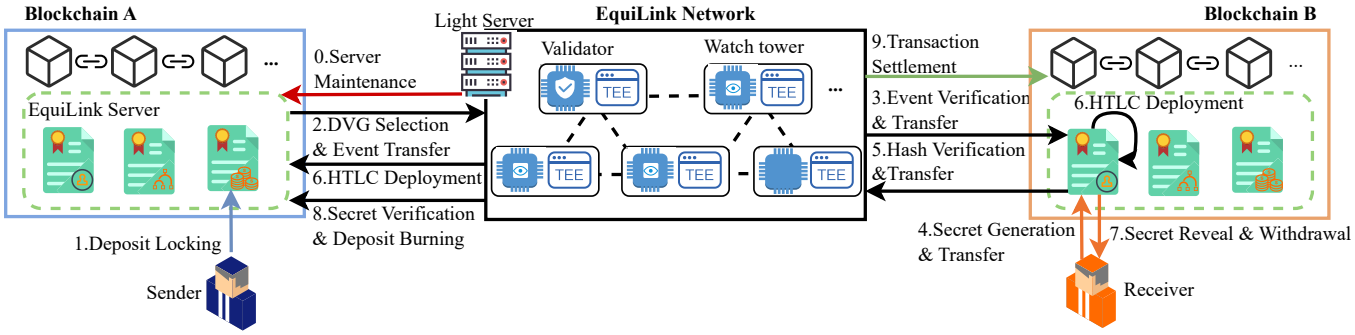


Fig. 2 The framework of EquiLink and the workflow of a cross-chain transaction, showing how the sender transfers tokens from Blockchain A to B.

participants $p$ forming a secure decentralized enclave network. This section presents the framework of EquiLink, while the protocol design and transaction workflow are detailed in Section V.

### B. EquiLink Service

The EquiLink Service is the on-chain component of EquiLink, responsible for transaction routing, staking, and cross-chain transaction execution. It is implemented through three core smart contracts: $C_{\text{router}}$, $C_{\text{staking}}$, and $C_{\text{tx}}$. As a blockchain-based component, it provides a decentralized and transparent foundation for cross-chain services without relying on a single trusted operator.

*1) Router Contract:* ($C_{\text{router}}$): This contract handles transaction routing, participant status management, and stores the IPFS address of the EquiLink source code for public verification. It provides the following functions:

- `router()`: Executes the routing process for transaction $t$ using a Keccak-256-based random function, $DVG(t) \leftarrow \text{router}(A_s, A_r, t_v, \text{Nonce})$, where $A_s$, $A_r$, and $t_v$ are transaction parameters, and Nonce represents uncontrollable randomness. The function outputs four active and eligible participants in $EN$ to form $DVG(t) = \{v, wt_i, wt_j, wt_k\} \subseteq EN$. An event is emitted to record the generated $DVG$.
- `updateStatus()`: Updates the participant status $p_{\text{status}} \in \{0, 1\}$, ensuring that only active participants ($p_{\text{status}} = 0$) remain eligible for subsequent validation rounds.

*2) Staking Contract:* ($C_{\text{staking}}$): This contract manages participants' staking balances $p_{\text{staking}}$. To participate in transaction validation, a participant must maintain sufficient stake such that $p_{\text{staking}} > t_{\text{fee}}$; only then can it join the transaction's $DVG$. The contract provides the following functions:

- `staking()`: Deposits $t_{\text{stake}}$ into $C_{\text{staking}}$, increasing $p_{\text{staking}}$ and making the participant eligible to join a $DVG$. An event is emitted to record the deposit.
- `withdraw()`: Withdraws $t_{\text{withdraw}}$ from $p_{\text{staking}}$, provided no pending transactions restrict the withdrawal. The balance is updated accordingly, and an event is emitted to record the withdrawal.

*3) Cross-Chain Transaction Contract:* ($C_{\text{tx}}$): This contract facilitates cross-chain transactions and provides the following functions:

- `transfer()`: Transfers tokens $t_v$ into the contract, invokes `router()` in $C_{\text{router}}$ to generate the $DVG$, and emits an event for cross-chain communication.
- `lock()`: Locks $t_v$ in $C_{\text{tx}}$ until the required conditions are satisfied.
- `mint()`: Mints $t_v$ on $BC_r$ after successful verification, allowing $A_r$ to withdraw with the correct secret $S$.
- `burn()`: Burns $t_v$ after finalization to maintain token-supply consistency and prevent double-spending.
- `createHTLC()`: Creates an HTLC for secure asset transfer.
- `checkTimeout()`: Checks whether transaction $t$ has timed out and triggers rollback if necessary.

### C. Light Server

The Light Server, as a third-party coordination service, with a set of trusted replicated attesters, provides a lightweight off-chain service to support the secure onboarding of public participants in the EquiLink bridge. Here, replicated attesters refer to a committee of attestation nodes that independently verify TEE attestation evidence during onboarding. They perform remote attestation of TEE-based participants and collectively maintain the trusted router list used by the router contract $C_{\text{router}}$. This mechanism ensures that only verified trusted participants can join the EquiLink Service, thereby maintaining the integrity of trusted participants through rigorous verification while preserving the decentralized nature of EquiLink.

To transform public participants into trusted participants, the system leverages a remote attestation mechanism. Each participant's TEE generates a verifiable attestation report (or "quote") that includes the measured hash of its execution environment, thereby demonstrating its integrity and authenticity. In addition, the process involves secure certificate management, endorsement verification, and compliance with predefined security policies. These features ensure that only participants with unaltered and properly configured TEE environments are admitted as trusted nodes in the network.

The attestation process begins when a participant launches its TEE-based application, which produces a local attestation report encapsulating the enclave measurement. The participant then sends this report to a remote attestation service (e.g., the Intel Attestation Service) for verification. Upon successful validation by the attestation authority, the signed report is submitted to the replicated attesters, which independently check it against the predefined security policies. A participant is enrolled as a trusted node in the EquiLink Network only when a majority of the replicated attesters approve the attestation result and jointly authorize its inclusion in the trusted router

list through signatures to the router contract $C_{\text{router}}$. This multi-step process ensures that only genuine and uncompromised TEEs participate, thereby enhancing overall network security.

### D. EquiLink Network

The EquiLink Network $EN$, composed of trusted participants, is designed to provide a secure decentralized network for cross-chain validation. To join the network, a participant must complete TEE remote attestation via the Light Server and stake tokens $p_{\text{staking}}$, thereby becoming a trusted participant $p \in EN$. This ensures that only verified and economically bonded participants contribute to cross-chain execution.

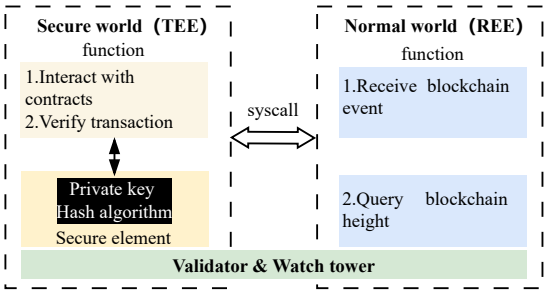


Fig. 3 The computing architecture of a trusted participant (built on a TEE).

As shown in Figure 3, trusted participants adopt a lightweight and stateless TEE architecture after joining the EquiLink Network. In this design, the enclave is only responsible for cross-chain transaction verification, while all system states and asset records remain stored on-chain. This ensures that TEEs do not replace blockchain consensus or state management, but only offload computationally expensive verification tasks.

Specifically, participants execute secure operations inside the **Trusted Execution Environment (TEE)**, including smart contract interactions and transaction verification. In the **Rich Execution Environment (REE)**, they monitor blockchain events and retrieve the current blockchain height for validation. This design preserves the blockchain trust model while improving efficiency.

When a transaction is initiated, the router contract $C_{\text{router}}$ randomly selects four TEE-based participants from $EN$ to form a $DVG$. Within each $DVG$, the validator $v$ and watchtowers $wt$ play different roles:

- **Validator** $(v)$: verifies the correctness of cross-chain transactions inside the TEE and submits the results via smart contracts. Formally, $v : t_{\text{status}} \rightarrow \{0, 1\}$, where $t_{\text{status}}$ denotes the transaction status.
- **Watchtower** $(wt)$: monitors the transaction state $t_{\text{status}}$, detects anomalies, and enforces penalties via smart contracts. Formally, $wt : t_{\text{status}} \rightarrow \{0, 1\}$, where *Failure* indicates a timeout or irregular behavior.

## V. Protocol Design

Section IV introduces the components and workflow of the EquiLink bridge. This section explains the EquiLink protocol using a representative cross-chain transaction example, as shown in Figure 2. To ensure atomic and verifiable cross-chain transactions while minimizing trust assumptions, EquiLink adopts an HTLC-based protocol anchored by TEEs and $DVG$. The protocol consists of following three phases: (i) **Initialization Phase** (Figure 4), where the replicated attesters in the Light Server authenticates TEE-based participants via remote attestation to establish trust and add the verified trusted participants to the trusted router list; (ii) **Transaction Phase** (Figure 5): $DVG$, based on TEEs, coordinates secure and atomic token transfers across chains and applies rewards and penalties to participants according to the economic model. This phase consists of three key processes: locking, transaction, and settlement, supported by EquiLink Service; and (iii) **Exit Phase** (Figure 6), where participants retrieve their stake, claim rewards, and safely exit the system.

### A. Initialization Phase

In the proposed system, any participant built on a TEE can join the EquiLink Network for reward, thereby enhancing both participation and transparency. The initialization workflow is illustrated in Figure 4. The process, which is jointly managed by the Light Server and EquiLink Service, consists of the following steps:

1) An untrusted participant retrieves and deploys the verification program from IPFS.
2) The participant submits a remote attestation request to the Light Server for verification. Once more than half of the replicated attesters approve the attestation result on-chain, the attestation is considered successful.
3) Upon successful attestation, the participant stakes tokens in the staking contract $C_{\text{staking}}$, ensuring that $p_{\text{staking}} > t_{\text{fee}}$ before proceeding.
4) The Light Server updates the router list in the router contract $C_{\text{router}}$, incorporating the new participant into the EquiLink Network.
5) The participant is officially registered in the system and can now be randomly assigned to a $DVG$ through the `router()` function, $DVG(t) \leftarrow \text{router}(A_s, A_r, t_v, \text{Nonce})$.

### B. Transaction Phase

The transaction phase forms the core of the EquiLink bridge. To facilitate secure and atomic token transfers across chains, we design an efficient HTLC-based protocol enhanced with TEEs. This phase consists of three main processes: the *locking process*, the *transaction process*, and the *settlement process*. The protocol flow is illustrated in Figure 5.

The overall process is as follows.

1) **Locking Process**:
   a) In this process, the user first authorizes the cross-chain transaction contract $C_{\text{tx}}$ by calling `approve`$(A_s, C_{\text{tx}}, t_v)$, where $A_s$ is the sender's address and $t_v$ is the token amount.

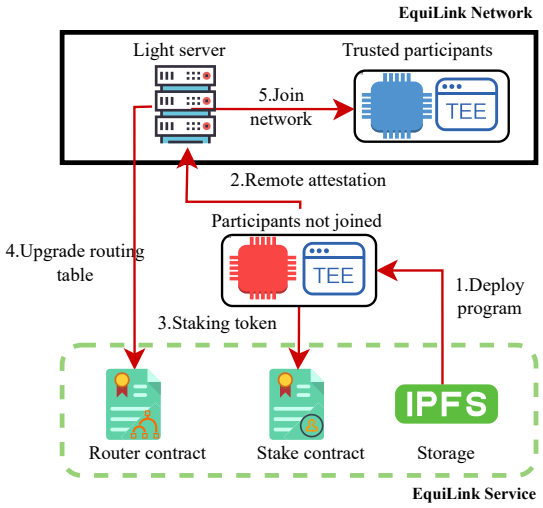


Fig. 4 The workflow of the initialization phase.

b) The user then initiates a cross-chain transaction by invoking the `transfer()` function of $C_{\text{tx}}$ with parameters `transfer`$(A_r, BC_r, t_v)$, and the contract subsequently executes `lock`$(t_v)$, where $A_r$ is the receiver's address, $BC_r$ is the target blockchain. Within the `transfer()` function, $C_{\text{tx}}$ calls the `router()` function of the routing contract $C_{\text{router}}$ to randomly select a $DVG$ $\{v, wt_i, wt_j, wt_k\}$.

2) **Transaction Process**:

a) `transfer()` triggers transaction:

$$t = (A_s, A_r, t_v, t_{id}, L, Nonce),$$

and generates event $M1 = (t, \mathcal{H}(t))$.

b) The validator $v$ receives $M1$ and queries the source blockchain $BC_s$ using the transaction identifier $t_{id}$ to retrieve the corresponding on-chain transaction record $t'$.

c) After verifying that $\mathcal{H}(t) = \mathcal{H}(t')$, the validator forwards $M1$ to Blockchain $BC_r$.

d) The contract $C_{\text{tx}}$ on $BC_r$ verifies whether $\mathcal{H}(t) \stackrel{?}{=} \mathcal{H}(t')$. If so, the receiver generates a secret $S$, computes $h_s = \mathcal{H}(S)$, and submits $h_s$ to $BC_s$ through the validator.

e) The validator builds `createHTLC`$(t_v, h_s)$ in $C_{\text{tx}}$. This function `createHTLC`$(t_v, h_s)$ emits an event: $M2 = \mathcal{H}(h_s, A_r, t_v, BC_r)$.

f) Upon receiving the `createHTLC` event $M2$, the validator verifies it by querying $M2$ on $BC_s$. If the verification fails, $C_{\text{tx}}$ triggers a refund to the sender.

g) If verification succeeds, the validator sends $M_2$ to $C_{\text{tx}}$ on $BC_r$ as a request for token minting.

h) On $BC_r$, $C_{\text{tx}}$ verifies:

$$M2 \stackrel{?}{=} \mathcal{H}(h_s, A_r, t_v, BC_r).$$

If verification is successful, the token is minted `mint`$(t'_v)$ and made available to receiver $A_r$ upon providing the secret $S'$; otherwise, $C_{\text{tx}}$ triggers a failure event, and the sender can execute `withdraw`$(t_v)$ to refund tokens $t_v$.

i) After the mint event, the validator forwards $S'$ to $BC_s$, where $C_{\text{tx}}$ verifies whether $h_s \stackrel{?}{=} \mathcal{H}(S')$. Upon successful verification, the token `burn`$(t_v)$ is executed on $BC_s$, and the validator is rewarded with $t_{\text{gas}}$.

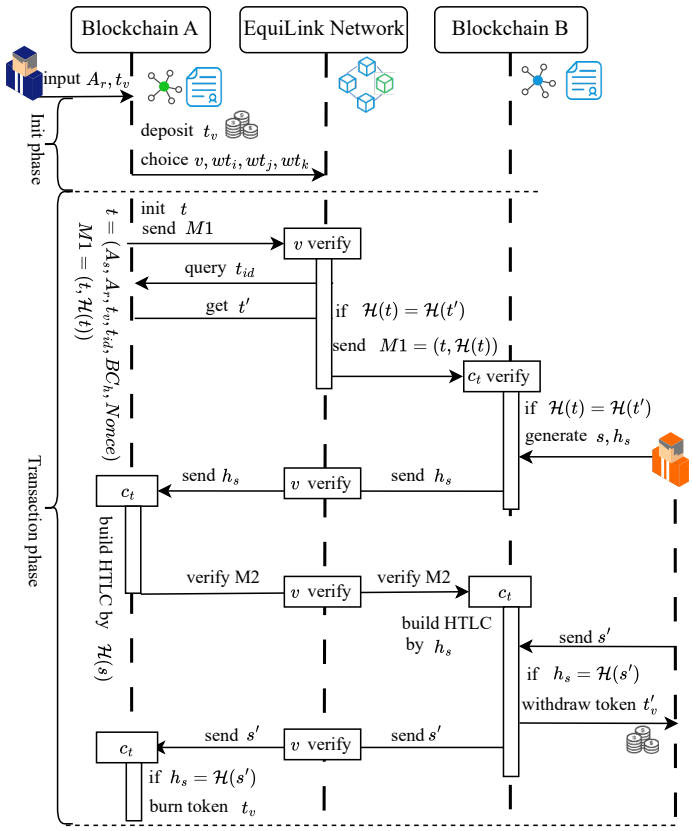


Fig. 5 The workflow of the transaction phase.

3) **Settlement Process**:

The settlement process determines the distribution of transaction fees $t_{\text{fee}}$ and penalties $t_{\text{punish}}$ to corresponding roles, based on the rules defined by the economic model and the confirmation deadline $\Delta L$. Each watchtower $wt \in \{wt_i, wt_j, wt_k\}$ starts a timer. If no transaction event is confirmed within $\Delta L$, the watchtowers query $BC_r$ for the secret $S$ and invoke `checkTimeout()` to determine whether transaction $t$ has timed out, thereby triggering a rollback if necessary.

- If the validator $v$ submits the transaction result within $\Delta L/2$, it receives $t_{\text{fee}}$.
- Watchtowers ($wt$) are allowed to submit results between $\Delta L/2$ and $\Delta L$. The first $wt$ to submit $S$ successfully before $\Delta L$ receives $t_{\text{fee}}$.
- If no valid result is submitted by $\Delta L$, two cases are considered:
  - *Case 1: No secret $S$ exists on $BC_r$*: The transaction is deemed unsuccessful due to external factors. The sender is refunded $t_v - t_{\text{gas}}$.
  - *Case 2: Secret $S$ exists on $BC_r$*: The failure is attributed to the validator $v$. Its staking balance is reduced to $p'_{\text{staking}} = p_{\text{staking}} - t_{\text{punish}}$, and the sender is compensated with $t'_v = t_v - t_{\text{gas}} + t_{\text{punish}}$.

This reflects a fail-safe design: when $S$ has appeared on $BC_r$ but the validator does not respond within $\Delta L$, the protocol conservatively attributes the failure to the validator in order to protect asset safety.

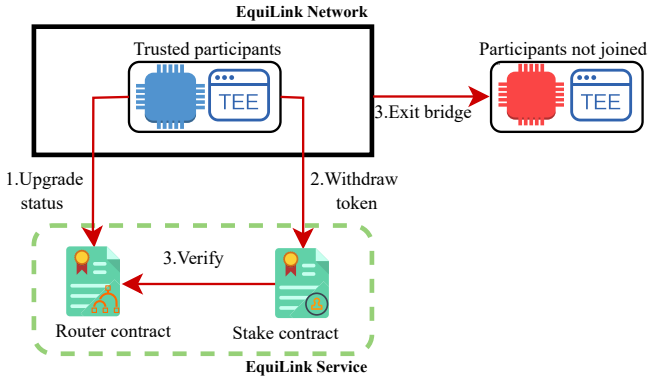


Fig. 6 The workflow of the exit phase.

### C. Exit Phase

When a participant $p \in EN$ decides to settle rewards and exit the system, the following steps, illustrated in Figure 6, are executed:

1) The participant updates their status to $p_{\text{status}} = 1$ on the routing contract $C_{\text{router}}$, indicating the intention to exit.
2) After confirming that no transactions are in progress, the participant invokes the `withdraw()` function on the staking contract $C_{\text{staking}}$ to cancel their stake and withdraw the entire staking balance $p_{\text{staking}}$.

EquiLink builds upon Hashed Time-Locked Contracts (HTLCs) but addresses their inherent limitations. In traditional HTLCs, timeouts often trigger rigid transaction failures and prolonged notification delays, especially if a node becomes unresponsive after receiving secret S. To mitigate these issues, EquiLink's dual-hash locking mechanism introduces the following advancements:

1) **Automated timeout arbitration**: In HTLC, the timeout arbitration step is initiated by the user. In EquiLink, this step is automated and initiated by the watchtower.
2) **Secondary Confirmation**: While HTLCs irreversibly abort upon signature failure, EquiLink allows a transaction to proceed if the minting event on $BC_r$ is finalized and $S$ is uploaded; otherwise, it executes a secure rollback.
3) **Simplified Routing Path**: EquiLink eliminates the multi-hop routing and cumulative time-lock redundancies of standard HTLCs. By deploying smart contracts directly on $BC_s$ and $BC_r$, the protocol streamlines interactions between the sender, validator, and receiver.

### D. Economic Model

To ensure the sustainability and fairness of the EquiLink bridge, we design an economic model that incentivizes honest participation and penalizes malicious behavior. Specifically, the model consists of a reward mechanism, which distributes the bridge fee $t_{\text{fee}}$ among honest participants $p_{\text{honest}}$, and a penalty mechanism, which deducts the staking amount $p_{\text{staking}}$ from participants responsible for transaction failures in order to compensate affected users.

The execution of this model is governed by the smart contracts within the EquiLink Service. The formal representation of the economic model is as follows:

- **Fee Allocation:**

$$\text{Fee}(t) = \begin{cases} v \mapsto t_{\text{fee}}, & \text{if } S \text{ is retrieved by } v, \\ wt \mapsto t_{\text{fee}}, & \text{if } S \text{ is retrieved by } wt, \\ A_s \mapsto t_v - t_{\text{gas}}, & \text{otherwise (refund).} \end{cases}$$

- **Penalty:**

$$\text{If } p \text{ is malicious}, \quad p'_{\text{staking}} = p_{\text{staking}} - t_{\text{punish}}, \quad (t_{\text{punish}} \geq t_{\text{fee}}),$$

where any unilateral deviation strictly reduces the deviator's expected payoff by at least a fixed positive margin $t_{\text{punish}}$. "deviator" denotes the party that chooses defection and thereby incurs the penalty. The execution of the economic model occurs at the final stage of the transaction phase, as detailed in Section 3, where we discuss the specific implementation methods.

## VI. Security Analysis

In this section, we first define the security properties that the system achieved. We then provide a formal analysis demonstrating that the proposed design satisfies these properties, followed by theoretical arguments showing that the system can withstand the representative attacks outlined earlier.

### A. Security Properties

Based on the proposed threat model in Section III-B, we now define the fundamental security properties that the system achieved. These properties serve as the foundation for the subsequent system security analysis.

*Definition 1 (Time-bounded Atomic Settlement):* A cross-chain transaction $t$ satisfies *time-bounded settlement* if, once initiated on the source chain $BC_s$ at block height $L_{\text{start}}$, it must be completed within a bounded block interval $\Delta L$. Specifically, by block height $L_{\text{end}} \leq L_{\text{start}} + \Delta L$, either the intended token value $t_v$ is successfully transferred to the receiver $A_r$ on the destination chain $BC_r$, or refunded to the sender $A_s$ on the source chain $BC_s$. Formally,

$$\exists\, L_{\text{end}} \leq L_{\text{start}} + \Delta L : \left[\text{Deliver}(t, A_r) \ \vee \ \text{Refund}(t, A_s)\right].$$

Intuitively, this property ensures that every cross-chain transaction terminates within $\Delta L$ blocks, achieving atomic completion (either delivery or refund).

*Definition 2 (Secret-preserving Security):* A cross-chain transaction $t$ satisfies *secret-preserving security* if the unlocking secret $S$ remains computationally hidden from any adversary $\mathcal{A}$ that does not complete the transaction successfully. Formally,

$$\Pr\left[\mathcal{A}(t, h_s) \to S \,\middle|\, t_{\text{status}} = 1\right] \leq \text{negl}(\lambda),$$

where $h_s$ is the hash commitment of $S$, and $\text{negl}(\lambda)$ denotes a negligible function in $\lambda$. Intuitively, this property ensures that the secret $S$ cannot be derived from on-chain information or any protocol transcript unless the transaction is successfully settled.

*Definition 3 (Exclusive Participants Authority):* A cross-chain transaction $t$ satisfies *exclusive participants authority* if only the designated participants assigned to $t$ are authorized to access or operate on the locked asset. Let $DVG(t)$ denote the set of participants assigned to $t$. Formally, for any requesting participant $p$, access is granted if and only if

$$p \in DVG(t) \quad \Longleftrightarrow \quad \text{Authorized}(p, t) = \text{true}.$$

Intuitively, this property ensures that no unauthorized participant can interfere with or claim the asset locked in the cross-chain transaction, providing strict access control for transaction execution.

*Definition 4 (Incentive Effectiveness):* Let $DVG(t)$ denote the designated participants for transaction $t$. Each $p \in DVG(t)$ chooses a strategy from $\{\mathsf{Cooperation}, \mathsf{Defection}\}$. Let $t_{\text{fee}} > 0$ be the per-transaction reward, $t_{\text{gas}} \geq 0$ denotes the operating cost (e.g., gas, computation), $t_{\text{punish}} \geq 0$ denotes any potential illicit gain from a successful deviation.

The per-transaction payoff of $p$ is

$$R_p = \begin{cases} t_{\text{fee}} - t_{\text{gas}}, & \text{if } \mathsf{Cooperation}, \\ t_{\text{fee}} - t_{\text{gas}} - t_{\text{punish}}, & \text{if } \mathsf{Defection}, \end{cases}$$

where $R_p$ represents the transaction fee-related gain (or loss) of participant $p$, $t_{\text{punish}} > 0$ is the on-chain penalty (deducted from the staked deposit $p_{\text{staking}}$).

### B. Security Proof

We formally analyze whether the proposed system satisfies the security properties defined in Section VI-A. To establish the overall security of the protocol, it is sufficient to prove Theorems 1–4.

**Theorem 1 (Time-bounded Atomic Settlement)** *If at least one honest participant $p$ in $DVG$, each cross-chain transaction $t$ achieves atomic completion within $\Delta L$ blocks, ensuring either successful delivery or full refund.*

*Proof.* See Appendix B for the proof. □

**Theorem 2 (Secret-preserving Guarantee).** *If at least one honest participant ($p_{honest} > 0$) exists in $DVG$, malicious actors cannot forge the secret $S$, thereby preventing asset theft.*

*Proof.* See Appendix C for the proof. □

**Theorem 3 (Exclusive Participants Authority Guarantee).** *For any cross-chain transaction $t$, only participants included in $DVG(t)$ are able to initiate, approve, or execute state transitions over the assets locked by $t$. Any participant $p \notin DVG(t)$ cannot influence the token flow of $t$ with non-negligible probability.*

*Proof.* See Appendix D for the proof. □

**Theorem 4 (Incentive Effectiveness Guarantee)** *For any designated participant and under other participants' strategies, choosing Honest yields a strictly higher expected payoff than Defection by a positive margin; consequently, the all-honest strategies forms a strict Nash equilibrium.*

*Proof.* See Appendix E for the proof. □

### C. Attack Resistance Analysis

Consistent with Section III-B, we assume an adversary that can corrupt a subset of participants (validators, watchtowers, and users), arbitrarily control the network, and compromise a subset of TEE-enabled participants (including potential side-channel leakage). However, the adversary cannot reverse finalized blockchain states, and the protocol remains secure as long as at least one honest participant exists in the selected $DVG$ for each transaction. We analyze the following attack types, leveraging **Theorems 1–4** and **Definitions 1–4**.

- **Double-Spending Attacks.**
  *Analysis.* By **Definition 1** (and **Theorem 1**), every cross-chain transaction $t$ must either deliver to $A_r$ on $BC_r$ or refund to $A_s$ on $BC_s$ within $\Delta L$, with no admissible intermediate state that both mints on $BC_r$ and retains locked value on $BC_s$. Hence conflicting spends cannot simultaneously succeed without violating atomic settlement.
- **Replay Attacks.**
  *Analysis.* Redeeming on $BC_r$ requires the preimage $S$ of $h_s$; by **Definition 2**, $S$ is computationally hidden unless the transaction legitimately completes. By **Definition 1**, expired HTLCs refund on $BC_s$ after $\Delta L$, so re-sending old messages cannot trigger a second valid redemption. Thus replay attempts fail except with negligible probability.
- **Compromised Participants.**
  *Analysis.* By **Theorem 3**, only designated participants $DVG(t)$ can authorize state transitions for $t$, thereby preventing unauthorized forgery or equivocation. Moreover, by **Theorem 4**, any deviation from the protocol results in strictly lower expected payoff due to on-chain slashing, making honest behavior incentive-compatible. Therefore, the randomized DVG selection mechanism provides strong robustness against partial participant compromise, ensuring correct progress as long as at least one honest participant is included in the selected $DVG$. The corresponding probability analysis is given in Appendix F.
- **Side-Channel Attacks.**
  *Analysis.* Suppose an adversary extracts information from a subset of TEEs through side-channel attacks. The leaked information may include the transaction identifier $t$, the verification messages $M_1, M_2$, and the secret value $S$. However, according to **Theorem 3**, each TEE only verifies its assigned transactions and cannot influence unrelated transactions across the network. Moreover, $t$ and $M_1, M_2$ are already publicly available on the blockchain for transaction validation, so their disclosure does not introduce additional security risks. Even if $S$ is exposed, the smart contract's access-control logic only allows it to determine whether the transaction is redeemed or refunded, and it cannot be used to steal assets arbitrarily. Any attempt to bypass the contract logic would violate the blockchain's consensus and finality guarantees. Therefore, side-channel leakage does not enable unauthorized asset creation or theft.
- **Physical Faults.**
  *Analysis.* Upon physical failure $t_{\text{status}} = 1$, watchtowers are part of $DVG(t)$ and, by **Definition 3**, are authorized to take over upon validator crashes/disconnections. Combined

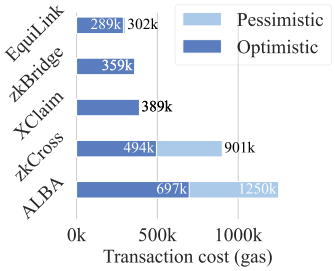


Fig. 7 Comparison of gas consumption between non-custodial bridges and EquiLink.

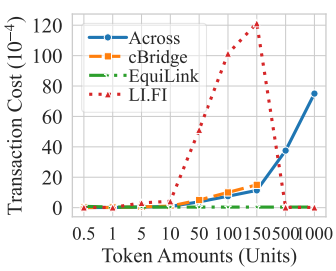


Fig. 8 Comparison of gas consumption between custodial bridges and EquiLink.

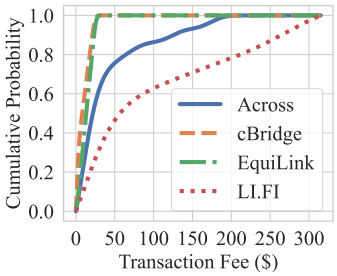


Fig. 9 Comparison of transaction fee CDF between custodial bridges and EquiLink.

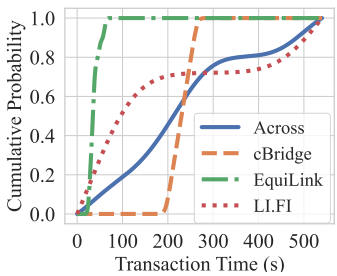


Fig. 10 Comparison of transaction time CDF between custodial bridges and EquiLink.

with **Definition 1** (and **Theorem 1**), they can either submit $S$ for delivery or trigger refund at timeout, ensuring that $t$ terminates within $\Delta L$ despite node failures.

## VII. Experimental Evaluation

This section presents the experimental setting and outlines the key metrics used to evaluate the performance of cross-chain bridges, including transaction cost, latency, economic model analysis, overall consumption, and security assessment. These metrics are critical for evaluating the effectiveness of cross-chain transactions and identifying key design challenges. The subsequent subsections provide a detailed elaboration of each metric.

### A. Experimental Setting

Six representative bridges were selected for evaluation based on their versatility and degree of decentralization, including two centralized bridges (Across Protocol, cBridge [14]) and four decentralized bridges (zkCross, ALBA, zkBridge, and XClaim). To improve the representativeness of the evaluation, we further included the cross-chain bridge aggregator LI.FI [35], which provides the best available routing option among multiple cross-chain bridges at the time of execution.

Experiments were conducted in two Ethereum-based environments. Across Protocol, cBridge, and LI.FI were evaluated in their real online environments using WETH-to-ETH transfers between Ethereum Mainnet and Arbitrum One. To ensure fair comparison, transactions on these platforms were initiated at the same time under the same network conditions, so that the quoted prices and execution environments were as consistent as possible. In contrast, zkCross, ALBA, zkBridge,and XClaim do not provide publicly accessible official platforms or complete deployable code for direct online testing. Therefore, after re-implementing these systems, we evaluated them on a local Ganache blockchain forked from Ethereum Mainnet under a unified experimental setup. The block generation time was fixed at 12 seconds.

### B. Transaction Cost

Transaction cost refers to the total cost of a cross-chain transaction, defined as $C = t_{\text{gas}} + t_{\text{fee}}$. It is a key factor that determines the potential for widespread user adoption of a cross-chain bridge. In this subsection, we take the cost of a single transaction as the baseline. Based on the experimental settings in Section VII-A, gas metrics are retrieved from live mainnet logs for online bridges and from execution traces for our re-implemented local baselines.

Figure 7 shows that EquiLink achieves lower gas costs than existing solutions, even under pessimistic execution conditions. Specifically, its gas consumption under pessimistic scenario is 14.1% lower than the optimistic scenario of the zkCross, demonstrating robustness across dispute scenarios. Figures 8 and 9 illustrate that EquiLink maintains stable gas consumption through a mint-and-burn design, with over 98% of transactions costing less than $25, demonstrating cost-effectiveness, particularly for high-value transfers.

### C. Transaction Latency

Transaction latency refers to the time elapsed from when the sender $A_s$ invokes the smart contract on chain $BC_s$ to when the receiver $A_r$ on chain $BC_r$ successfully receives the token $v$. It is a critical metric for evaluating cross-chain bridges, as it has a direct impact on user experience and system security during transaction settlement periods. To ensure the accuracy of our latency evaluation, we conducted 10 independent experiments for each token amount ranging from 0.1 ETH to 500 ETH, and averaged the results to minimize environmental noise.

Figure 10 illustrates the cumulative distribution function (CDF) of transaction confirmation times. As shown, EquiLink significantly outperforms the other three, with most transactions confirmed within 36 seconds, while the others all exceed 240 seconds. Figure 12 compares transaction latencies across different token amounts, where EquiLink consistently achieves the lowest latency and maintains stable performance between 28 and 37 seconds regardless of token amounts. Across and LI.FI exhibit increasing latency with token amounts, reaching up to 900 and 540 seconds, respectively, for large transfers. Figure 11 further breaks down the end-to-end latency of EquiLink into approximately 12 seconds on the source chain, 0.5 seconds for off-chain processing, and 24 seconds on the aim chain, reduces the average cross-chain transaction latency by 18.9%. These findings demonstrate that EquiLink provides more predictable and scalable latency performance, making it particularly suitable for real-time or high-frequency cross-chain interactions.

### D. Economic Model Analysis

To analyze the economic model of the cross-chain bridge, we employ a game-theoretic approach to understand the strategic interactions among various participants.

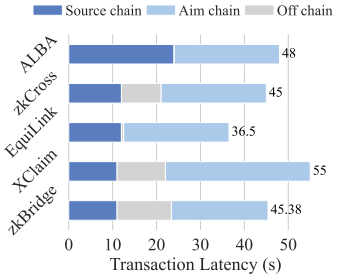


Fig. 11 Comparison of transaction latency between non-custodial bridges and EquiLink.

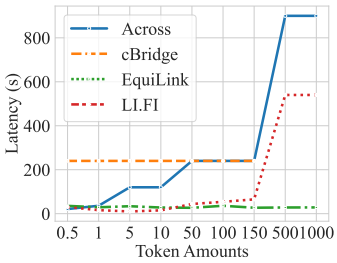


Fig. 12 Comparison of transaction latency between custodial bridges and EquiLink.

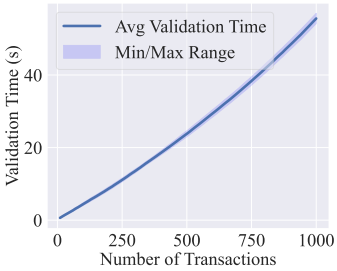


Fig. 13 Validation time for varying numbers of transactions.

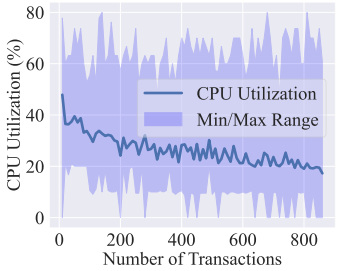


Fig. 14 CPU Utilization for varying numbers of transactions.

*1) Model Setup:* We define the gain model in the cross-chain bridge as a constant-sum game, because the participants, namely the validator and watchtowers, compete over the allocation of the fixed total fee $t_{\text{fee}}$. Each participant aims to maximize its own gain while minimizing the gains of others. The game is expressed as $\sum_{p=1}^{n} R_p = t_{\text{fee}}$, where $R_p$ represents the transaction fee-related gain (or loss) of participant $p$, and $n$ is the number of players included in the game model.

The key components and players in the game are defined as follows: the players consist of a validator $v$ and a representative watchtower $wt$, and each player can choose one of two strategies, namely Cooperation (C) or Defection (D).

We list the assumptions made in the model as follows: (i) the validator and watchtower have two possible behaviors, namely cooperation and defection; (ii) if the validator cooperates, the watchtower determines whether it needs to intervene in the event of validator failure or misbehavior; and (iii) in the event of a failure, the watchtower takes over to determine the cause and distribute penalties or rewards accordingly.

*2) Game Representation:* Let $x$ denote the strategy profile vector of the players. The validator's and watchtower's payoffs are derived from the transaction fee $t_{\text{fee}}$, which is provided by the sender. The corresponding payoff matrix is shown in Table I.

TABLE I Payoff matrix between validator (v) and watchtower (wt).

| v \ wt | C | D |
|---|---|---|
| **C** | $(t_{\text{fee}}, 0)$ | $(t_{\text{fee}}, 0)$ |
| **D** | $(-t_{\text{punish}}, t_{\text{fee}})$ | $(0, 0)$ |

*3) Equilibrium Analysis:* For the validator, cooperating yields a higher payoff than defecting, as $t_{\text{fee}} > t_{\text{punish}}$. For the Watchtower, if the validator defects, cooperating yields a payoff of $t_{\text{fee}}$, which is strictly greater than the zero payoff from defection, i.e., $t_{\text{fee}} > 0$. Therefore, the strategy profile (C, C) forms a Nash equilibrium because neither the validator nor the watchtower can improve their payoff by unilaterally changing their strategy. Any unilateral deviation strictly reduces the deviator's expected payoff by at least a fixed positive margin $t_{\text{punish}}$. Cooperation ensures the most efficient and secure operation of the cross-chain bridge, aligning with the incentives for all participants and achieving system sustainable economic model.

*4) Economic Attack Analysis:* EquiLink provides both protocol-level and incentive-level protection against economic attacks such as stake griefing, bribery, and fee manipulation. First, as discussed in Section V-D, fee allocation is separated from punishment, so transaction failure alone does not imply validator loss, while slashing applies only to malicious behavior. Second, the game model in Table I shows that honest cooperation yields higher payoff than malicious deviation when the punishment is sufficiently high. Third, the randomized DVG selection mechanism increases the difficulty of bribery and collusion, while the fixed smart-contract fee rule limits the room for fee manipulation. A more detailed discussion is provided in Appendix G.

### *E. Overall Consumption*

Overall consumption measures the total resource cost and performance of participants in the EquiLink Network. A lower entry barrier, reflected in reduced consumption and performance requirements, promotes broader participation and enhances the system's scalability and decentralization. To comprehensively evaluate the system's overall consumption, we evaluate the resource cost associated with *System Initialization*, *Node Joining*, and *Node Exiting*, as well as the performance impact during *Transaction Validation*, including latency and CPU utilization.

*1) System Initialization:* The total cost for initializing the system includes deploying all the decentralized components, with gas costs detailed in Table II. While the initialization cost is approximately 3.6 million gas, it is a one-time expense that provides decentralized services for all users, making it a justified and cost-efficient investment.

*2) Node Joining Costs:* When a new node joins the system, it incurs gas costs associated with staking and adding itself to the router list, as outlined in Table II. The total gas cost of 158,746 for node entry is equivalent to around 7-8 typical Ethereum transactions, which is quickly recouped through rewards earned from validating cross-chain transactions.

*3) Node Exiting Costs:* Exiting the system involves updating the routing contract to mark the node as inactive and withdrawing the staked amount. The gas costs for these actions are summarized in Table II. The total exit cost is comparable to approximately 3 Ethereum transactions, which can be typically offset by the node's earnings from participating in the network.

*4) Performance of Transaction Validation:* Validation time and CPU utilization reflect device performance requirements and thus influence the entry barriers to participation. We evaluate both metrics for off-chain transaction validation as the number of transactions increases from 1 to 1000. Experiments

TABLE II Gas consumption for system initialization, node joining, and node exiting.

| System Initialization | | Node Joining | | Node Exiting | |
|---|---|---|---|---|---|
| **Component/Action** | **Gas Consumption** | **Action** | **Gas Consumption** | **Action** | **Gas Consumption** |
| Routing Contract | 956,682 | Node Staking ETH | 65,967 | Updating Routing Contract | 33,561 |
| Staking Contract | 783,535 | Adding to Router List | 92,779 | Withdrawing Staked Token | 31,179 |
| HTLC Contract for Sender | 471,830 | | | | |
| HTLC Contract for Receiver | 1,390,830 | | | | |
| **Total: 3,602,877** | | **Total: 158,746** | | **Total: 64,740** | |

were conducted on an Alibaba Cloud server with 4 CPU cores and 16 GB of RAM, with the TEE environment executed on Intel SGX.

Figure 13 shows that the average validation time increases with the number of transactions, while remaining smooth and stable without abrupt jumps or performance collapse. This suggests that the TEE-based validation process maintains steady processing behavior in the evaluated range, without approaching the EPC-limit-induced bottlenecks in our experiments. Figure 14 shows that CPU utilization remains at a moderate level during continuous execution. Overall, the average CPU load stays relatively low and does not exhibit sustained growth with the number of transactions, suggesting only limited continuous CPU overhead during long-running operation.

### *F. Security Assessment*

Given that cross-chain bridges involve asset transfers, it is essential to assess the resilience of EquiLink. We conducted experiments that replicated several critical attack vectors: smart contract vulnerabilities, key/attestation compromise, replay attacks and physical attacks. Our security assessment framework integrates simulated adversarial environments and formal verification results.

*1) Resistance to Smart Contract Vulnerabilities:* We analyzed the implemented HTLC contracts using established auditing tools, including Slither and related security testing frameworks. The findings were limited to implementation-level best-practice issues, and we revised the contract code accordingly following secure coding guidelines. This suggests that, although protocol design can reduce the attack surface at the system level, smart contract vulnerabilities are not automatically eliminated by the protocol itself and still require careful attention from developers.

*2) Resistance to Key/Attestation Compromise:* For key compromise, we focus on the transaction phase and examine the success probability under randomized DVG selection, as shown in Figure 15. The results show that, for a fixed malicious ratio $\rho$, a larger DVG size $K$ leads to a higher transaction success rate, because the probability that the selected DVG contains at least one honest participant increases with $K$. However, as analyzed in Section VI-C and Appendix F, even if the keys of all selected DVG members are compromised, the impact is still bounded to degraded liveness, such as transaction failure or timeout, rather than unauthorized asset transfer. Therefore, key compromise may degrade liveness, but it does not violate asset safety.

For attestation compromise, we focus on the initialization phase and evaluate the compromise success rate under different attester numbers $N$, as shown in Figure 16. The results show that increasing the number of attesters reduces the probability that a forged attestation can pass the majority-based admission rule, because an adversary must compromise more attesters to exceed the threshold. This confirms that the replicated-attester design improves robustness against attestation compromise. Moreover, even when attestation compromise occurs and a malicious participant is admitted, the impact is still mainly limited to reduced admission reliability rather than direct system failure or cross-chain transaction failure.

*3) Resistance to Replay Attacks:* Replay attacks occur when a malicious actor intercepts and retransmits valid cross-chain transaction data, potentially causing duplicate asset transfers. In this experiment, each transaction is repeated twice with identical events: M1 and M1' (from $BC_s$ to $BC_r$) and M2 and M2' (from $BC_r$ to $BC_s$). The system's response is tested by having the $C_{\text{tx}}$ contract at $BC_r$ store and validate the transaction ID ($t_{id}$), ensure only one instance (either M1 or M1') is accepted while duplicates are rejected.

Data were collected from 10 attack batches, with the number of repeat transactions per batch increasing from 2 to 20. The success rates in handling repeated transactions for M1 and M2 are plotted in Figure 17. Results show that both M1 and M2 effectively prevent replay attacks, with M1 generally performing better. The system maintains high resilience, though success rates decrease as the transaction volume rises. This decline is not due to replay attack failures but rather contract invocation failures under high concurrency due to Ganache.

*4) Resistance to Physical Faults:* In addition to traditional software threats, participants $p \in EN$ are also vulnerable to physical faults like network disconnections or power outages, which can lead to participant failures during transaction execution.We validated this approach through an experiment simulating a physical attack scenario, where the validator $v$ and Watchtowers $wt_1, wt_2, wt_3$ were abruptly disconnected during transaction execution. Specifically, we considered five representative cases, **Case 1:** the validator $v$ disconnects after the transaction secret $s$ has been submitted to $BC_r$; **Case 2:** the validator $v$ disconnects before the secret $s$ is submitted; **Case 3:** the validator $v$ and one watchtower disconnect simultaneously; **Case 4:** a majority of participants disconnect, for example due to a large-scale outage; and **Case 5:** a complete network outage in the extreme case.

As shown in Figure 18, in cases 1-4, as long as at least one participant is functional, the Watchtower can still complete the transaction. A small number of revocations occurred due to timeout $L_{\text{end}} - L_{\text{start}} > \Delta L$, demonstrating resilience to physical threats. In the extreme Case 5, where all participants disconnect, the sender can still withdraw assets, ensure no asset loss.

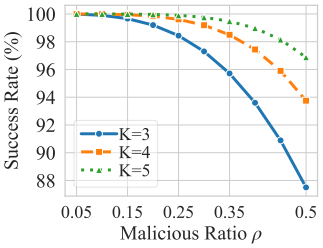


Fig. 15 Transaction success rate under key compromise for different DVG sizes $K$ and malicious ratios $\rho$.

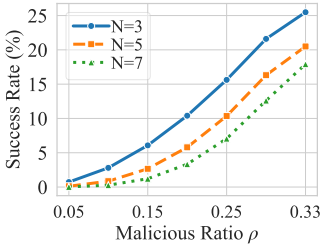


Fig. 16 Attestation compromise success rate under different attester numbers $N$ and malicious ratios $\rho$.

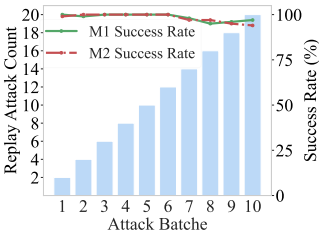


Fig. 17 Comparison of replay attack counts and success rates for M1 and M2 across different attack batches.

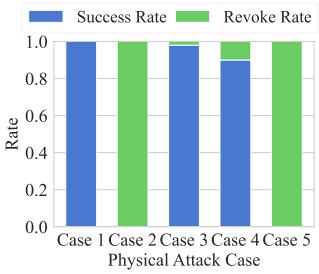


Fig. 18 Comparison of success and revoke rates across different physical faults cases.

## VIII. Discussion

### A. Limitations

The EquiLink bridge addresses several challenges by mitigating asset custody risks and single points of failure in centralized bridges through a decentralized network. In addition, by performing off-chain computation with on-chain verification, it significantly reduces transaction costs and latency compared to fully decentralized bridges. However, the current design still has limitations that warrant further investigation and refinement.

The existing scheme does not provide privacy protection for transactions, as all transaction details remain fully transparent on the blockchain. Although this transparency is beneficial for auditability and verifiability, it may be undesirable in privacy-sensitive application scenarios, such as confidential business transactions, privacy-preserving financial activities, or cases where users do not wish their transaction relationships and asset flows to be publicly exposed. Second, although the design of EquiLink is in principle compatible with multiple blockchain systems, the current implementation and evaluation still focus mainly on EVM-compatible environments, and support for heterogeneous chains remains limited. Extending it to non-EVM chains and Layer-2 rollup systems still requires further protocol adaptation.

### B. Future Work

One promising direction for future work is to enhance the privacy protection of EquiLink transactions. A potential solution is to integrate ZKPs to conceal transaction details while still ensuring correctness and verifiability. By using ZKPs, the bridge could enable private cross-chain transactions where neither the transaction amount nor the sender/receiver identities are publicly disclosed.

Another important direction for future work is to extend EquiLink to broader heterogeneous blockchain systems, including non-EVM chains and Layer-2 rollups. Although its architecture is in principle compatible with multiple blockchains, further protocol adaptation is still needed to support diverse execution and verification models in practice, so that EquiLink can serve as a more general underlying layer for cross-chain interoperability.

## IX. Conclusion

In this paper, we presented EquiLink Bridge, a novel semi-custodial cross-chain architecture that systematically balances efficiency, decentralization, and security. By leveraging TEE-based trusted off-chain computation, EquiLink effectively reduces transaction costs by 14.1% and latency by 18.9% compared to existing solutions, achieving cost- and latency-efficient cross-chain performance. To further promote decentralization, EquiLink introduces a lightweight decentralized service and verification network that enables rapid node joining and exiting, while maintaining a minimal validation workload, thereby significantly lowering the entry barriers for participants and preserving security guarantees. Through the integration of atomic cross-chain transaction protocols and economic incentive models, EquiLink enhances resistance against replay attacks, physical attacks, and other potential threats, achieving a 100% success/revocation rate for cross-chain asset transfers. Overall, EquiLink offers a promising pathway toward achieving efficient, decentralized, and secure cross-chain interoperability.

## Acknowledgments

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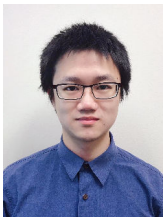

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## APPENDIX

**Adversarial model.** $\mathcal{A}$ may corrupt all but one DVG participant, control the network, and exploit contract logic, but cannot break the assumption: **Blockchain finality** means that once a block is finalized on the blockchain, it cannot be reverted or altered by any future consensus decisions, even under adversarial control of the network. **Preimage resistance** of a hash function $\mathcal{H}(\cdot)$ means that, given an input $x$, it is computationally infeasible for any probabilistic polynomial-time (PPT) adversary to find a distinct input $x' \neq x$ such that $\mathcal{H}(x') = \mathcal{H}(x)$. **TEE security** means that honest and uncompromised TEEs provide integrity, confidentiality, and remote attestation guarantees. Consistent with Section refsubsec:threat-model, we do not assume that all TEEs remain uncompromised: an adversary may compromise a subset of TEE-enabled participants or attempt side-channel leakage. The protocol-level security therefore relies on blockchain finality and the assumption that at least one honest participant exists in the selected $DVG$ for each transaction.

### A. Additional Tables

TABLE III Key notations used in the system model.

| Notation | Description |
|---|---|
| $BC_s$ | Source chain where the sender account is located. |
| $BC_r$ | Destination chain where the receiver account is located. |
| $L_{\text{start}}$ | Block ledger height when the transaction starts. |
| $L_{\text{end}}$ | Block ledger height when the transaction finishes. |
| $\Delta L$ | Maximum block ledger height difference allowed before the Hashed Time-Locked Contract (HTLC) transaction times out. |
| $t_{id}$ | Unique identifier of a transaction. |
| $t$ | Transaction from the sender account to the cross-chain transaction contract. |
| $t_{\text{status}}$ | $t_{\text{status}} \in \{0, 1\}$ Status indicator of transaction $t$, where 0 denotes success and 1 denotes failure. |
| $t_v$ | Token value at the start of the transaction. |
| $t'_v$ | Token value at the end of the transaction. |
| $t_{\text{fee}}$ | Transaction fee received by the participants. |
| $t_{\text{gas}}$ | Gas fee incurred by on-chain computation. |
| $t_{\text{punish}}$ | Penalty for a validator due to transaction failure. |
| $\mathcal{H}(\cdot)$ | Cryptographic hash function $\mathcal{H}(\cdot)$ mapping an arbitrary-length input to a fixed-length digest of $\lambda$ bits. |
| $S$ | Secret (preimage) chosen by the receiver. |
| $h_s$ | Hash commitment of the secret, defined as $h_s = \mathcal{H}(S)$, used in HTLC. |
| $\lambda$ | Security parameter determining the hash output length and negligible probability bound. |
| $\text{negl}(\lambda)$ | Negligible function in the security parameter $\lambda$. |
| $M_1$ | Transaction metadata passed from $BC_s$ to the validator. |
| $M_2$ | HTLC-related metadata passed from $BC_s$ to the validator. |
| $C_{\text{router}}$ | Router contract for participant assignment, synchronized on all blockchains. |
| $C_{\text{staking}}$ | Staking contract for managing participant deposits. |
| $C_{\text{tx}}$ | Cross-chain transaction contract, deployed on each blockchain. |
| $A_s$ | Address of the sender. |
| $A_r$ | Address of the receiver. |
| $v$ | Validator responsible for cross-chain verification. |
| $wt_i$ | $i$-th watchtower node for monitoring transactions. |
| $p_{\text{staking}}$ | Staked token amount of the participant. |
| $p_{\text{status}}$ | The operational status flag of the participant, where 0 indicates active and 1 indicates offline or exited. |
| $Nonce$ | On-chain randomness (e.g., `prevrandao`). |

### B. Time-bounded Atomic Settlement Proof

Any violation of Time-bounded Atomic Settlement implies one of the following:

1) *Unpaid delivery:* $A_r$ receives assets on $BC_r$ without $A_s$ being debited on $BC_s$. This requires $C_{\text{tx}}$ on $BC_r$ to accept an opening of $h_s$ before the lock transaction is finalized on $BC_s$. Such an attack either (i) forges a preimage of $h_s$ contradicting the preimage resistance of $\mathcal{H}$ or (ii) falsifies the relayed state, violating blockchain finality or TEE integrity.
2) *Unrefunded lock:* $A_s$'s assets are locked on $BC_s$ but neither delivered nor refunded on $BC_r$. However, $C_{\text{tx}}$ enforces a timeout $\Delta L$; the honest DVG participant ensures the timeout condition is evaluated, triggering a refund on $BC_s$ within $\Delta L$ blocks. Network control alone cannot prevent this due to blockchain finality.
3) *Secret censorship:* $\mathcal{A}$ suppresses the relay of $S$ to $BC_r$ to prevent redemption. Nevertheless, the honest DVG node eventually submits $S$ (once revealed by $A_r$), enabling redemption before $\Delta L$ expires, or the timeout triggers refund.

In all cases, *Time-bounded Atomic Settlement* holds except with negligible probability under the stated assumptions. □

### C. Secret-related Asset Safety Proof

Suppose, for contradiction, that a PPT adversary $\mathcal{A}$ succeeds in causing unauthorized asset transfer by forging or manipulating the secret $S$, thereby violating the guarantee in Theorem 2. Such a success can only occur in one of the following cases:

1) *Hash-based forgery:* $\mathcal{A}$ outputs a value $S' \neq S$ such that $\mathcal{H}(S') = h_s$. This directly breaks a standard hash assumption, namely the preimage resistance of $\mathcal{H}$, which holds except with probability at most $\text{negl}(\lambda)$.
2) *Commitment or chain-state manipulation:* $\mathcal{A}$ tampers with $h_s$, the verification path, or the transaction state recorded on-chain in order to make an invalid secret appear valid. Such an attack necessarily contradicts the blockchain finality assumption, since it requires modifying already committed contract state or accepted transaction metadata on $BC_s$ or $BC_r$.

Therefore, if $\mathcal{A}$ succeeds in using $S$ to cause unauthorized asset transfer, it must either (i) break a standard hash assumption or (ii) contradict blockchain finality assumptions. Under these assumptions, the success probability of $\mathcal{A}$ is at most $\text{negl}(\lambda)$. Hence, no PPT adversary can violate the guarantee in Theorem 2 except with negligible probability. □

### D. Exclusive Participants Authority Proof

We now show that only authorized participants can satisfy the authentication predicate $\mathsf{Auth}(\cdot)$. If an adversary $\mathcal{A}$ succeeds in performing any state transition without authorization, it must do one of the following:

1) *Bypass contract enforcement:* Subvert the contract logic of $C_{\text{tx}}$ to accept an unauthorized call. Since the access control logic is enforced by the smart contract and finalized on-chain, any such bypass would require

altering a finalized blockchain state, thereby violating the **blockchain finality** assumption.

2) *Forge evidence:* Produce a valid attestation or consensus proof without executing the authorized enclave or achieving quorum finality—thereby violating the **TEE security** assumption.

Therefore, *Exclusive Participants Authority* also holds with overwhelming probability.

Combining the above cases, we conclude that the protocol achieves the *Exclusive Participants Authority Guarantee*. □

### *E. Incentive Effectiveness Proof*

1) *Compliance with contract logic:* In this case, we use game-theoretic analysis to show that cooperation yields the maximum payoff and constitutes a Nash equilibrium in VII-D.
2) *Bypass contract enforcement:* Subvert the contract logic of $C_{\text{tx}}$ to accept an unauthorized call. Since the access control logic is enforced by the smart contract and finalized on-chain, any such bypass would require altering a finalized blockchain state, thereby violating the **blockchain finality** assumption.

Since Cooperation is a strictly dominant strategy for the validator and watchtowers under the above assumptions, any defection strictly reduces the deviator's expected payoff by at least a fixed positive margin $t_{\text{punish}}$. (set by the fee/slashing parameters on $C_{\text{staking}}$). Hence the all-honest strategy profile is a *strict* Nash equilibrium. Moreover, because deviations do not improve payoffs and are penalized on chain, the mechanism is incentive-effective as claimed. □

### *F. Probability Analysis of Compromised Participants*

Let $\rho$ denote the fraction of compromised participants in the system. Following the standard Byzantine fault tolerance assumption widely adopted in distributed systems, we assume $\rho \leq \frac{1}{3}$. Under this setting, the probability that all $K$ selected DVG members are compromised is upper bounded by

$$\Pr[\text{fail}] \leq \rho^K,$$

and thus the probability that a transaction is assigned at least one honest participant is at least

$$\Pr[\text{succ}] \geq 1 - \rho^K.$$

For example, when $\rho = \frac{1}{3}$, if $K = 4$ then

$$\Pr[\text{succ}] \geq 1 - \left(\frac{1}{3}\right)^4 \approx 98.77\%,$$

and if $K = 5$ then

$$\Pr[\text{succ}] \geq 1 - \left(\frac{1}{3}\right)^5 \approx 99.59\%.$$

These results support the claim in the main text that randomized DVG selection provides strong robustness against partial participant compromise.

### *G. Analysis of Economic Attacks*

EquiLink provides both protocol-level and incentive-level protection against economic attacks, including stake griefing, bribery, and fee manipulation. The following discussion complements the economic model in Section V-D.

1) *Stake griefing.* EquiLink separates fee allocation from punishment. Under the fee-allocation rule, $t_{\text{fee}}$ is awarded to the validator if $S$ is retrieved by $v$, and to the watchtower if $S$ is retrieved by $wt$; otherwise, the sender $A_s$ receives a refund. Under the penalty rule, slashing is triggered only when a participant is judged malicious, with the staking amount reduced by $t_{\text{punish}}$, where $t_{\text{punish}} \geq t_{\text{fee}}$. Hence, transaction failure alone does not imply validator loss. Moreover, validators never take custody of user assets, so their stake exposure is bounded and does not scale with the transferred asset amount, which limits the effectiveness of stake-griefing attacks.
2) *Bribery.* According to Table I, cooperation yields higher payoff than defection when the punishment is sufficiently high. For the validator, cooperation yields $t_{\text{fee}}$, whereas malicious deviation leads to a penalty of $-t_{\text{punish}}$ once detected. For the watchtower, if the validator defects, cooperation yields $t_{\text{fee}}$, which is greater than the zero payoff from defection. In addition, the DVG is selected randomly for each transaction, which reduces the adversary's ability to pre-identify target participants and increases the cost of bribery or collusion.
3) *Fee manipulation.* EquiLink adopts a fixed and transparent transaction-fee rule through smart contracts. As a result, service providers cannot arbitrarily modify bridge fees, quoted prices, or routing fees during protocol execution. Since users can also check the transaction status according to $t_{id}$, the transparency of the fee and transaction process is further improved, which constrains the room for fee manipulation.