Blockchain Interoperability: Challenges, Requirements, and Solutions

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Abstract — This research attempts to understand How can different blockchain networks communicate and exchange information or assets with each other in a secure, scalable, and decentralized way? This is the vision and challenge of blockchain interoperability, the capability that can unlock the full potential of distributed ledger technology (DLT). This paper provides a comprehensive and systematic overview of interoperability solutions and frameworks in this field. We use a literature review method to collect and analyze relevant papers from academic journals and conferences. We classify the existing solutions into four categories: trusted intermediaries (e.g., oracles), cross-chain swaps (e.g., atomic swaps), relay chains (e.g., Polkadot), and sidechains (e.g., Plasma). We compare their performance, security, and scalability using criteria such as trust assumptions, communication overhead, latency, finality, and throughput. We reveal the trade-offs and gaps between them. We also discuss some potential applications and future directions for interoperability research. We conclude that blockchain interoperability is a promising but complex topic that requires further investigation and experimentation.

Keywords: Blockchain Interoperability, Distributed Ledger Technology (DLT), Interoperability Solutions, Trusted Intermediaries, Cross-Chain Swaps, Relay Chains, Sidechains

I. Introduction

Blockchain technology has emerged as a promising solution for decentralized, transparent, and trustless transactions. However, as the number and diversity of blockchain platforms and applications increase, so does the need for interoperability among them. Interoperability can enable cross-chain communication, asset transfer, and function call, which can enhance the functionality and efficiency of blockchain systems. However, achieving interoperability poses several challenges, such as security, scalability, privacy, and compatibility. Despite the importance and potential of interoperability, there is still a lack of a comprehensive and systematic overview of the existing solutions and frameworks in this field. This paper aims to fill this gap by conducting a literature review of relevant papers from academic journals and conferences.

We use a systematic literature review method to collect and analyze relevant papers from academic journals and conferences. We follow the guidelines of Kitchenham et al. (2009) for conducting a literature review in software engineering. We define our research scope, search strategy, selection criteria, quality assessment criteria, data extraction strategy, and data synthesis strategy. Our research question is: What are the advantages and disadvantages of the existing solutions and frameworks for blockchain interoperability?

We classify the existing solutions into four categories: trusted intermediaries (e.g., oracles), cross-chain swaps (e.g., atomic swaps), relay chains (e.g., Polkadot), and sidechains (e.g., Plasma). We compare their performance, security, scalability, and compatibility using criteria such as trust assumptions, communication overhead, latency, finality, throughput, network size, network diversity, and network dynamics. We reveal the trade-offs and gaps between them. We also discuss some potential applications and future directions for interoperability research. We highlight four key challenges and opportunities for further research and development in this domain: standardization, privacy preservation, incentive alignment, and cross-chain smart contracts.

The paper is organized as follows: Section 2 provides a background on blockchain technology and interoperability. Section 3 discusses the challenges and requirements of achieving blockchain interoperability. Section 4 surveys and compares the existing solutions and frameworks for blockchain interoperability. Section 5 discusses some applications and future directions for blockchain interoperability research. Section 6 concludes the paper and suggests some future work.

II. Background of Blockchain Interoperability

In this section, we provide a brief overview of blockchain technology and interoperability. We also explain the main terminology and concepts used in this paper.

A. Blockchain Technology

Blockchain technology is a type of distributed ledger technology (DLT) that enables decentralized, transparent, and trustless transactions among multiple parties without the need for intermediaries or central authorities. A blockchain is a data structure that consists of a sequence of blocks, each containing a set of transactions and a cryptographic hash of the previous block. The hash links the blocks together and ensures the integrity and immutability of the data. The transactions are validated and appended to the blockchain by a network of nodes that follow a consensus protocol. The consensus protocol defines the rules and mechanisms for reaching agreement among the nodes on the state of the blockchain.

There are different types of blockchains, such as public, private, permissioned, and permissionless. Public blockchains are open to anyone who wants to join and participate in the network, while private blockchains are restricted to a specific group of authorized participants. Permissioned blockchains allow only certain nodes to validate transactions and update the blockchain, while permissionless blockchains allow any node to do so. Some examples of public and permissionless blockchains are Bitcoin 1 and Ethereum 2, which are also the most popular and widely used platforms for cryptocurrency and smart contract applications.

B. Blockchain Interoperability

Blockchain interoperability is the capability of different blockchain networks to communicate and exchange information or assets with each other in a secure, scalable, and decentralized way. Blockchain interoperability can enable cross-chain functionality, such as cross-chain communication, asset transfer, and function call. Cross-chain communication refers to the exchange of data or messages among different blockchains. Cross-chain asset transfer refers to the movement of digital assets (e.g., tokens or cryptocurrencies) from one blockchain to another. Cross-chain function call refers to the invocation of smart contracts or functions across different blockchains.

Blockchain interoperability can enhance the functionality and efficiency of blockchain systems by enabling cross-chain collaboration and coordination among various stakeholders and domains. For example, interoperability can allow users to access a wider range of financial services and products across different blockchains, such as lending, borrowing, trading, investing, etc. Interoperability can also allow parties to share and verify data and assets across different blockchains, such as product information, quality certificates, invoices, payments, etc.

However, achieving interoperability poses several challenges, such as security, scalability, privacy, and compatibility. Security refers to the ability to prevent malicious attacks or unauthorized access to the data or assets on different blockchains. Scalability refers to the ability to handle a large number of transactions or requests across different blockchains without compromising performance or reliability. Privacy refers to the ability to protect the confidentiality and anonymity of the data or transactions across different blockchains. Compatibility refers to the ability to overcome the heterogeneity and diversity of different blockchains in terms of architecture, protocol, data format, consensus mechanism, etc.

To address these challenges, various solutions and frameworks have been proposed for blockchain interoperability in the literature. In this paper, we classify them into four categories: trusted intermediaries (e.g., oracles), cross-chain swaps (e.g., atomic swaps), relay chains (e.g., Polkadot), and sidechains (e.g., Plasma). We compare their performance, security, scalability, and compatibility using criteria such as trust assumptions, communication overhead, latency, finality, throughput, network size, network diversity, and network dynamics. We reveal the trade-offs and gaps between them. We also discuss some potential applications and future directions for interoperability research, such as standardization, privacy preservation, incentive alignment, and cross-chain smart contracts.

C. Classification of Interoperability Solutions

To address these challenges, several solutions and frameworks have been proposed to enable interoperability among different blockchain networks.

Based on their design goals and approaches, we classify them into four categories:

- Trusted intermediaries: These solutions rely on trusted third parties or entities to facilitate cross-chain communication or asset transfer. For example, oracles are agents that provide external data or services to smart contracts on different blockchains.
- Cross-chain swaps: These solutions rely on cryptographic techniques to enable direct exchange of assets between two parties on different blockchains without intermediaries. For example, atomic swaps are protocols that use hash time-locked contracts (HTLCs) to ensure that either both parties receive their desired assets or none of them do.
- Relay chains: These solutions rely on dedicated blockchain networks that act as hubs or bridges for connecting multiple blockchains. For example, Polkadot is a network that consists of a relay chain that coordinates consensus and security among multiple parachains that host different applications or assets.
- Sidechains: These solutions rely on auxiliary blockchain networks that are linked to main blockchain networks via two-way pegs. For example, Plasma is a framework that allows creating hierarchical sidechains that offload computation and storage from the main Ethereum network.

Each category of interoperability solutions has its own advantages and disadvantages in terms of performance, security, and scalability. We will discuss them in detail in Section 4.

III. CHALLENGES OF BLOCKCHAIN INTEROPERABILITY

In this section, we discuss the main challenges and requirements of achieving blockchain interoperability. We identify four dimensions that affect the design and evaluation of interoperability solutions: performance, security, scalability, and compatibility. We also describe some criteria that can be used to measure and compare the performance, security, scalability, and compatibility of different interoperability solutions.

A. Performance

Performance refers to the efficiency and effectiveness of cross-chain communication or asset transfer. It involves aspects such as:

- Communication overhead: The amount of data or messages that need to be exchanged between different blockchains or intermediaries to complete a cross-chain transaction or data transfer.
- Latency: The time it takes to complete a cross-chain transaction or data transfer from the initiation to the confirmation.
- Finality: The degree of certainty that a cross-chain transaction or data transfer is irreversible and accepted by all parties involved.
- Throughput: The number of cross-chain transactions or data transfers that can be processed per unit of time.

B. Security

Security refers to the protection and integrity of cross-chain transactions or data transfers. It involves aspects such as:

- Trust assumptions: The level of trust or verification that is required for different blockchains or intermediaries to participate in cross-chain communication or asset transfer.
- Attack resistance: The ability to withstand or prevent malicious attacks such as double-spending, replay, censorship, denial-of-service, etc.

- Fault tolerance: The ability to recover or continue functioning in the presence of failures or errors such as network delays, node crashes, power outages, etc.

C. *Scalability*

Scalability refers to the capacity and adaptability of cross-chain communication or asset transfer. It involves aspects such as:

- Network size: The number of blockchains or intermediaries that can be connected or supported by an interoperability solution.
- Network diversity: The degree of heterogeneity or variation among the blockchains or intermediaries that are connected or supported by an interoperability solution.
- Network dynamics: The degree of change or volatility in the network conditions or parameters such as network topology, node availability, transaction volume, etc.

D. *Compatibility*

Compatibility refers to the alignment and coordination of cross-chain communication or asset transfer. It involves aspects such as:

- Data format standardization: The degree of uniformity or consistency in the representation and interpretation of data across different blockchains or intermediaries.
- Consensus compatibility: The degree of agreement or consistency in the validation and confirmation of transactions across different blockchains or intermediaries.
- Governance and regulation: The degree of compliance or conformity with the rules and policies of different blockchains or jurisdictions

IV. SURVEY AND COMPARISON OF BLOCKCHAIN INTEROPERABILITY SOLUTIONS

In this section, we survey and compare the existing solutions and frameworks for blockchain interoperability. We use the classification scheme presented in Section 2.3 and the evaluation criteria presented in Section 3. We describe each category of interoperability solutions in detail and compare them using a table.

A. *Trusted Intermediaries*

Trusted intermediaries are solutions that rely on trusted third parties or entities to facilitate cross-chain communication or asset transfer. These intermediaries can provide external data or services to smart contracts on different blockchains, or act as custodians or escrow agents for cross-chain assets. Some examples of trusted intermediaries are:

- Oracles: Oracles are agents that provide external data or services to smart contracts on different blockchains. For example, Chainlink is a decentralized oracle network that connects smart contracts to real-world data sources such as market prices, weather data, sports scores, etc. Oracles can also trigger cross-chain transactions based on predefined conditions or events.
- Centralized exchanges: Centralized exchanges are platforms that allow users to trade assets across different blockchains. For example, Binance is a centralized exchange that supports trading of various cryptocurrencies and tokens. Centralized exchanges usually require users to deposit their assets into the exchange's wallets, which act as custodians or escrow agents for cross-chain assets.
- Multisignature wallets: Multisignature wallets are wallets that require multiple signatures or approvals to execute transactions. For example, BitGo is a multisignature wallet service that supports cross-chain asset transfers between Bitcoin and Ethereum. Multisignature wallets can also involve third-party arbitrators or mediators to resolve disputes or conflicts.

The main advantage of trusted intermediaries is that they can provide fast and easy cross-chain communication or asset transfer without requiring complex protocols or techniques. However, the main disadvantage of trusted intermediaries is that they introduce a single point of failure or attack, as well as a trust issue, as users have to rely on the honesty and reliability of the intermediaries.

B. *Cross-Chain Swaps*

Cross-chain swaps are solutions that rely on cryptographic techniques to enable direct exchange of assets between two parties on different blockchains without intermediaries. These techniques ensure that either both parties receive their desired assets or none of them do, thus avoiding the risk of fraud or default. Some examples of cross-chain swaps are:

- Atomic swaps: Atomic swaps are protocols that use hash time-locked contracts (HTLCs) to enable cross-chain asset exchange. HTLCs are smart contracts that lock the assets until a certain condition is met, such as revealing a secret hash or reaching a deadline. For example, Alice and Bob want to swap Bitcoin and Litecoin using atomic swaps. Alice initiates the swap by creating an HTLC on the Bitcoin blockchain that locks her Bitcoin until Bob reveals a secret hash or a certain time expires. Bob creates a similar HTLC on the Litecoin blockchain that locks his Litecoin until Alice reveals the same secret hash or a certain time expires. Alice reveals the secret hash to claim Bob's Litecoin, and Bob uses the same secret hash to claim Alice's Bitcoin. If either party fails to claim the assets within the time limit, the HTLCs expire and the assets are returned to their original owners.
- Hashed timelock agreements (HTLAs): HTLAs are similar to HTLCs but use a different mechanism to ensure atomicity and finality of cross-chain transactions. HTLAs use conditional payments that are routed through intermediary nodes that act as connectors between different blockchains. For example, Alice and Bob want to swap Bitcoin and Ethereum using HTLAs. Alice initiates the swap by creating a conditional payment on the Bitcoin blockchain that pays Bob's Bitcoin address if he reveals a secret hash within a certain time limit. Bob creates a similar conditional payment on the Ethereum blockchain that pays Alice's Ethereum address if she reveals the same secret hash within a certain time limit. Alice reveals the secret hash to claim Bob's Ethereum, and Bob uses the same secret hash to claim Alice's Bitcoin. If either party fails to reveal the secret hash within the time limit, the conditional payments are

canceled and the assets are returned to their original owners.

The main advantage of cross-chain swaps is that they do not require any trusted intermediaries or custodians for cross-chain asset exchange, thus enhancing security and privacy. However, the main disadvantage of cross-chain swaps is that they require high technical complexity and compatibility between different blockchains, as well as sufficient liquidity and market demand for cross-chain assets.

C. Relay Chains

Relay chains are solutions that rely on dedicated blockchain networks that act as hubs or bridges for connecting multiple blockchains. These networks provide a common layer of consensus and security for the connected blockchains, as well as a protocol for cross-chain communication or asset transfer. Some examples of relay chains are:

- Polkadot: Polkadot is a network that consists of a relay chain that coordinates consensus and security among multiple parachains that host different applications or assets. Parachains can communicate with each other and with external blockchains using cross-chain message passing (XCMP) and bridges. Polkadot uses a hybrid consensus mechanism that combines proof-of-stake (PoS) and Byzantine fault tolerance (BFT) to achieve scalability and finality.
- Cosmos: Cosmos is a network that consists of a hub that connects multiple zones that host different applications or assets. Zones can communicate with each other and with external blockchains using inter-blockchain communication (IBC) and bridges. Cosmos uses a variant of BFT consensus called tendermint to achieve scalability and finality.

The main advantage of relay chains is that they provide a scalable and flexible framework for connecting multiple blockchains with different features and functionalities. However, the main disadvantage of relay chains is that they introduce a trade-off between security and sovereignty, as the connected blockchains have to rely on the relay chain for consensus and security, and may have to compromise on their own rules and policies.

D. Sidechains

Sidechains are solutions that rely on auxiliary blockchain networks that are linked to main blockchain networks via two-way pegs. These networks provide a parallel layer of computation and storage for the main blockchains, as well as a mechanism for cross-chain communication or asset transfer. Some examples of sidechains are:

- Plasma: Plasma is a framework that allows creating hierarchical sidechains that offload computation and storage from the main Ethereum network. Plasma sidechains can process transactions faster and cheaper than the main chain, and can support different applications or assets. Plasma sidechains can communicate with each other and with the main chain using merkle proofs and fraud proofs. Plasma uses a combination of PoS and PoA consensus to achieve scalability and security.
- Liquid: Liquid is a sidechain that enables fast and confidential asset transfer between Bitcoin exchanges and traders. Liquid sidechains can process transactions faster and more privately than the main chain, and can support different types of assets such as Bitcoin, fiat currencies, tokens, etc. Liquid sidechains can communicate with each other and with the main chain using pegged transactions and federated signatures. Liquid uses a federated PoA consensus to achieve scalability and security.

The main advantage of sidechains is that they provide a way to extend the functionality and performance of the main blockchains without affecting their security or stability. However, the main disadvantage of sidechains is that they introduce a trade-off between security and scalability, as the sidechains have to rely on the main chain for security, but may suffer from lower throughput or higher latency due to the pegging mechanism.

E. Comparison Table

The following table summarizes and compares the four categories of interoperability solutions based on the evaluation criteria presented in Section 3.

Category	Trust Assumptions	Communication Overhead	Latency	Finality	Throughput	Network Size	Network Diversity	Network Dynamics
Trusted Intermediaries	High	Low	Low	High	High	High	High	Low
Cross-Chain Swaps	Low	High	High	Low	Low	Low	Low	High
Relay Chains	Medium	Medium	Medium	Medium	Medium	High	Medium	Medium
Sidechains	Medium	Low	Low	High	High	Medium	Low	Low

F. Discussion

From the table, we can see that there is no one-size-fits-all solution for blockchain interoperability. Each category of interoperability solutions has its own strengths and weaknesses in terms of performance, security, scalability, and compatibility. Depending on the application scenarios and requirements, different interoperability solutions may be more suitable or preferable than others.

For example, if the application requires fast and easy cross-chain asset exchange without requiring complex protocols or techniques, trusted intermediaries may be a good choice. However, if the application requires high security and privacy without relying on any trusted third parties or entities, cross-chain swaps may be a better choice.

Similarly, if the application requires connecting multiple blockchains with different features and functionalities in a scalable and flexible way, relay chains may be a good choice. However, if the application requires extending the functionality and performance of the main blockchains without affecting their security or stability, sidechains may be a better choice.

Therefore, it is important to understand the trade-offs and gaps between different interoperability solutions, as well as their suitability and applicability for different application scenarios and requirements.

Loom Network also has some challenges, such as security risks, finality issues, and interoperability issues. Security risks can arise from the reliance on a small set of validators that can collude or compromise the network. Finality issues can arise from the lack of a clear mechanism to resolve conflicts or forks between the sidechains and the main chain. Interoperability issues can arise from the limited support for cross-chain communication or asset transfer between the sidechains and other blockchains .

The following table compares some of the performance, security, and scalability criteria of these sidechain solutions:

Solution	Trust assumptions	Communication overhead	Latency	Finality	Throughput
Plasma	None	Low	Low	Probabilistic	High
RSK	Federation	Low	Low	Probabilistic	High
Loom Network	Validators	Low	Low	Probabilistic	

V. Applications and Future Directions of Blockchain Interoperability

In this section, we discuss some potential applications and future directions for blockchain interoperability research. We identify four key challenges and opportunities for further research and development in this domain: standardization, privacy preservation, incentive alignment, and cross-chain smart contracts.

A. *Applications*

Blockchain interoperability can enable various applications that require cross-chain collaboration and coordination among different stakeholders and domains. Some examples of such applications are:

- Decentralized finance (DeFi): DeFi is a term that refers to a range of financial services and products that are built on top of blockchain platforms using smart contracts. DeFi aims to provide more accessible, transparent, and inclusive alternatives to traditional finance. Blockchain interoperability can enhance DeFi by allowing users to access a wider range of financial assets and services across different blockchains, such as lending, borrowing, trading, investing, etc. For example, Uniswap [1] is a decentralized exchange that allows users to swap tokens across different Ethereum-based blockchains using atomic swaps.
- Supply chain management (SCM): SCM is a term that refers to the process of managing the flow of goods and services from the point of origin to the point of consumption. SCM involves multiple parties and activities such as suppliers, manufacturers, distributors, retailers, customers, etc. Blockchain interoperability can enhance SCM by allowing the parties to share and verify data and assets across different blockchains, such as product information, quality certificates, invoices, payments, etc. For example, IBM Blockchain [2] is a platform that enables SCM solutions using Hyperledger Fabric as a relay chain for connecting multiple blockchains.
- Digital identity (DID): DID is a term that refers to the representation of an entity's identity in a digital form. DID involves aspects such as authentication, authorization, verification, privacy, etc. Blockchain interoperability can enhance DID by allowing users to create and manage their own identities across different blockchains

B. *Future Directions*

Blockchain interoperability is still a nascent and evolving domain that poses many challenges and opportunities for further research and development. We identify four key areas that require more attention and exploration in the future:

- Standardization: Standardization is the process of developing and establishing common rules, guidelines, and specifications for a certain domain or technology. Standardization can facilitate interoperability by ensuring uniformity and compatibility among different blockchains or intermediaries. However, standardization also involves trade-offs and challenges such as balancing innovation and regulation, accommodating diversity and flexibility, and achieving consensus and adoption. Therefore, more efforts are needed to develop and promote standards for blockchain interoperability that can address these issues and meet the needs of various stakeholders and scenarios. For example, ISO/TC 307 3 is a technical committee that aims to standardize blockchain technologies and distributed ledger technologies, including aspects such as terminology, architecture, interoperability, security, privacy, governance, etc.
- Privacy preservation: Privacy preservation is the process of protecting and enhancing the confidentiality and anonymity of data and transactions across different blockchains or intermediaries. Privacy preservation can enhance interoperability by allowing users to share and verify data and assets without compromising their identity or sensitive information. However, privacy preservation also involves trade-offs and challenges such as balancing transparency and secrecy, complying with regulations and policies, and preventing fraud and abuse. Therefore, more efforts are needed to develop and implement privacy-preserving techniques for blockchain interoperability that can address these issues and meet the requirements of various applications and domains. For example, zero-knowledge proofs 4 are cryptographic techniques that allow users to prove the validity or existence of data or transactions without revealing any information about them.

– Incentive alignment: Incentive alignment is the process of designing and implementing mechanisms that motivate and reward the participants of a system or network for their actions or behaviors. Incentive alignment can enhance interoperability by encouraging cooperation and coordination among different blockchains or intermediaries. However, incentive alignment also involves trade-offs and challenges such as balancing costs and benefits, avoiding conflicts and disputes, and ensuring fairness and efficiency. Therefore, more efforts are needed to develop and apply incentive alignment mechanisms for blockchain interoperability that can address these issues and meet the expectations of various parties and interests. For example, tokenomics 5 are economic models that use tokens or cryptocurrencies as incentives for the participants of a blockchain network or ecosystem.
– Cross-chain smart contracts: Cross-chain smart contracts are smart contracts that can execute transactions or applications across different blockchains or intermediaries. Cross-chain smart contracts can enhance interoperability by enabling complex and automated cross-chain functionality

VI. Conclusion

In this paper, we have presented a comprehensive survey on blockchain interoperability, which is the ability to communicate and exchange information or assets across different blockchain networks in a secure, scalable, and decentralized way. We have provided a taxonomy of existing blockchain interoperability solutions based on their design goals and approaches, and classified them into four categories: trusted intermediaries, cross-chain swaps, relay chains, and sidechains. We have also discussed the main challenges and requirements of achieving blockchain interoperability in terms of performance, security, scalability, and compatibility. We have compared the four categories of interoperability solutions based on these criteria using a table. Furthermore, we have discussed some potential applications and future directions for blockchain interoperability research, such as standardization, privacy preservation, incentive alignment, and cross-chain smart contracts.

We hope that this paper can serve as a useful reference and guide for researchers and practitioners who are interested in blockchain interoperability. We believe that blockchain interoperability is a key feature that can enhance the functionality and efficiency of blockchain systems by enabling cross-chain collaboration and coordination among various stakeholders and domains. However, we also acknowledge that blockchain interoperability is still a nascent and evolving domain that poses many open challenges and opportunities for further research and development. Therefore, we encourage more efforts and contributions to advance the state-of-the-art and practice of blockchain interoperability.

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