Journal of Information Systems Engineering and Management
2025, 10(20s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Interoperable Blockchain Frameworks: Enabling Cross-Chain Transactions in Global Ecosystems

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ARTICLE INFO

Received: 24 Dec 2024

Revised: 31 Jan 2025

Accepted: 16 Feb 2025

ABSTRACT

The overall purpose of this research is to consider the considerations and design of many blockchain structures in digital international environments for smooth cross-chain operations. This work investigates the problems and possibilities involving the enhancement of interoperability of blockchains together with various sectors like healthcare, decentralized finance, and individual energy management. In the context of the same, the current study shall employ four different blockchain algorithms where the same interoperability protocols shall be measured based on parameters like efficiency, security, and scalability across the nodes. Outcomes reveal that the proposed framework improved transaction velocity by 35%, cut transaction costs by 20% ad heightened data security by 40% as reviewed to centralized structural styles. This study also demonstrates that cross-chain solutions are effective for scalability as decentralized applications run across different chains. The research shows that despite the fact that major advancements have been observed regarding cross-chain communication, other issues, including consensus synchronization and network protection remain issues that require solutions. Anatomy of these outcomes raises the awareness about the need to adhere to standards, and to build safe approaches to consensus needed to increase the share of holistic blockchain platforms. Cultivating practical awareness of interoperability in blockchain is as important as extending the real-life application of blockchain in a global environment by increasing data exchange, reducing operating expenses, ensuring safe and transparent transactions, and improving data exchange.

Keywords: Blockchain Interoperability, Cross-Chain Transactions, Decentralized Finance, Healthcare, Distributed Ledger Technology.

I. INTRODUCTION

Blockchain technology has become widespread with its comprehensible and objective digital platforms for numerous uses across finance, supply chain, medical procedures, and voting. However, one of the largest issues concerning blockchain technology is the existence of poor compatibility between blockchain platforms [1]. Each blockchain is an isolated system containing some protocols, consensus models, and structural patterns that do not allow smooth interoperability and transactions between distinct blocks [2]. This silo mentality hampers the potential growth and utility of blockchain technology to create an environment that can only be complemented with linked and interconnected entities.

The difference will be solved by means of the interconnected blockchain solutions that will provide the opportunity for crossing and making transactions from one blockchain to another [3]. Indeed, such frameworks are very valuable for the progress of the combined world blockchain environment that works for various purposes but remains separate chains. As for industries like finance with common use of multiple currencies and cross-border payments and supply chain utilizing data sharing between multiple organizations, it is crucial to provide safety and efficiency of cross-chain operations. This research examines the work being done to design and implement blockchain systems that accept transactions across blockchains. Through review of existing technologies such as atomic swaps, blockchain bridges, and multi-chain protocols and analysis of the challenges with respect to security, scalability, and standardization, the present study aims to derive factors that are likely to influence interoperability. In addition to the above, the implications of interoperability on the blockchain ecosystem at large also become a subject of investigation as to how it impacts scalability, adoption, and innovation. Finally, this research will provide actionable knowledge and recommend a strong framework, thereby enabling interconnected blockchain systems to be the catalyst in the next wave of technological development of blockchain technology and the integration of the next-generation digital economy.

II. RELATED WORKS

There have been many explorations of blockchain interoperability in the management of electronic health records (EHR). Ferreira et al. [15] made an in-depth review on how DLT can better the interoperability and security of EHRs. Their work puts emphasis on the fact that blockchain-based solutions should be used in secure sharing of healthcare data from one system and organization to another, all the while observing data privacy. The authors discuss the problems and potential benefits of applying blockchain in healthcare systems, outlining the role of smart contracts and secure consensus mechanisms that allow for secure, real-time data sharing between stakeholders. In the context of the Metaverse and virtual reality, Fiaz et al. [16] introduced a framework known as MetaSSI, which would ensure enhanced personal data protection, cybersecurity, and privacy for users in Metaverse-based platforms. The framework applies blockchain to ensure safe user data management and thereby enhances control over personal information. This approach aims to make virtual reality platforms more interoperable by allowing users to access data across multiple virtual environments and sharing it seamlessly, along with robust privacy and security measures. Another key area of research in the blockchain is Decentralized Finance, or DeFi. DeFi was discussed by Gramlich et al. [17] who offered modern state of the decentralized financial systems and outlined potential research directions for it in terms of multivocality of the literature review. They also talk of the communication within the blockchain networks for the Defi systems in which users can be able to perform cross-chain transactions and they acquire various forms of financial services across various platforms. The study pulls out that enhancing cross-chain communication is going to be vital for DeFi's future development and mainstream adaption. Harvey and Rabetti [18] also define Decentralised Finance (DeFi) within the sphere of international business, explaining how blockchain will help businesses execute transactions across national borders without the help of financial middlemen. That is why authors assume that the further development of the international financial integration process will depend more on the enhancement of the compatibility of blockchain technologies and the optimization of the expenses for products exchange. There is another set of substantial applications for blockchain interoperability that concerns the distributed energy systems management. It is proposed that Henninger and Mashatan [21] demonstrated an architecture for the control of distributed renewable energy using blockchain. They explain how through blockchain, integration of renewable electricity sources in smart grids can be accomplished as well as secure and efficient electric energy trading. In their opinion, the capability of performing transactions and messages between holders of different Blockchain platforms will enable smooth interaction of various producers, consumers and service providers of decentralized energy systems. Apart from that, Khan et al. [24] also focus on the collaborative role of blockchain, AI, and IoT in digitalizing small and medium-sized enterprises. The focus has been on the need for interoperability among blockchain to allow the easy communication of IoT devices with AI systems and blockchain networks. The authors further propose that with the integration of blockchain and AI and IoT, the data exchange between different networks will be increased, which will make the industries, such as manufacturing and supply chain management, function more efficiently and securely. In the supply chain management sector, blockchain is being considered to enhance the transparency, traceability, and efficiency of supply chains. Khan et al. [25] conduct a systematic risk analysis of supply chain operations and how blockchain can minimize such risks. The authors argue that interoperability of blockchain systems can improve the management of supply chains because stakeholders will be able to access shared data and take informed decisions. In the agricultural sector, Krithika [26] conducts a review of blockchain applications for improving traceability of food and the efficiency of the supply chain. This author addresses the possibilities blockchain presents to bring about transparency in agricultural processes while sharing secure real-time data between diverse systems. Interoperability is also considered in relation to effects that blockchain may bring to farmers, suppliers and consumers to be in a better collaborative system through which the stakeholders in any level will be given necessary information at the right time.

III. METHODS AND MATERIALS

Data Collection

In this research, secondary data were collected from research papers, whitepapers, and reports spanning the subject of Blockchain connectivity. Real-world data were also collected from the raw transaction data of cross-chain real-world applications on main net via API log of open-source blockchains [4]. Other measures defined in the dataset include cross-chain transaction time, cross-chain transaction cost as well as success rates from cross-chain operations. The data traces from the cross-chain transactions that occurred in different networks such as Ethereum, Bitcoin, and both Polkadot, and Cosmos helped in evaluating this interoperability. This dataset was used for benchmarking the performance of various practical solutions in the field of interoperability to facilitate the assessment of which algorithms contribute to maximizing the efficiency and security of cross-chain operations [5].

Selected Algorithms

Within the scope of this research paper, four crucial algorithms applicable to blockchain interoperability are chosen for deep analysis: It is befitting to review an understanding of Atomic Swaps, Blockchain Bridges, Interledger Protocol (ILP), and Polkadot's XCMP (Cross-Chain Message Passing) algorithm in detail [6]. All these have been used in order to create safe efficient interaction of chains through cross chain communication and transactions. Describing each of these algorithms one by one:

1. **Atomic Swaps**

Atomic swaps are cross-chain trading which excludes the use of a third party because it allows the two parties to directly form a trade contract in two different blockchains. This algorithm has a-consensus principle that means a transaction is either delivered fully on both chains or is rolled back in their entirety to prevent any loss in assets that would occur due to an unsuccessful transaction. It uses hash time-locked contracts where the transaction occurs after a set time and only when the two parties meet the required benchmarks [7].

Key Features:

- Peer-to-peer exchange between varying blockchains.
- Cryptographic mechanism to ensure trust.
- A time-bound and failsafe mechanism to protect both the parties.

Working:

- The party A initiates by creating an HTLC in Blockchain A, locking down the assets under a time lock.
- The party B creates a corresponding HTLC on Blockchain B, locking the assets in similar terms and conditions.
- When both parties carry out their respective steps the transaction gets executed.
- If the conditions are not met by the time limit, the deal fails and the assets each party owns are retained [8].

Table 1: Example of Atomic Swap Transaction

Blockchain A (Sender)	**Blockchain B (Receiver)**	**Swap Amount (BTC)**	**Swap Amount (ETH)**	**Time Limit (Hours)**
Alice	Bob	1 BTC	10 ETH	24
Charlie	Dave	0.5 BTC	5 ETH	12

"function atomic_swap(BlockchainA, BlockchainB, senderA, receiverB):

Generate secret_key

Create HTLC on BlockchainA with secret_key

Create HTLC on BlockchainB with same secret_key

if condition_met:

Release assets on both blockchains

else:

Revert transaction and return assets to users"

2. **Blockchain Bridges**

Blockchain bridges facilitate intercommunication between various blockchain networks and transfer tokens or data from one blockchain to another. They are middlemen that provide trust and security when cross-chain operations take place. A bridge operates by locking the assets on one chain and minting a corresponding token on the other chain. The process works by unlocking the assets when the token is returned on the original blockchain [9].

Key Features:

- It enables the transfer of assets from one blockchain to another.
- Acts as a secure intermediate between two networks
- It can be applied to both token and data transfer mechanisms.

Working:

- A user sends assets through an application to the bridge smart contract on Blockchain A.
- It locks the assets at that side and gives out the corresponding token on Blockchain B.
- Once it finds a token, it releases the original assets.

Table 2: Example of Blockchain Bridge Transaction

Source Blockchain	**Target Blockchain**	**Tokens Locked (ETH)**	**Tokens Minted (BTC)**	**Fee (%)**
Ethereum	Bitcoin	5	0.25	0.5
Polkadot	Cosmos	3	0.15	0.3

"unction blockchain_bridge(sourceChain, targetChain, user, amount):

lock_assets(sourceChain, user,

```
amount)
  mint_tokens(targetChain, user, amount)
  if return_tokens:
    unlock_assets(sourceChain, user)
  else:
    rollback_transaction"
```

3. **Interledger Protocol (ILP)**

The Interledger Protocol (ILP) aims to facilitate interoperability between different payment networks. A layer is set on top of existing blockchains to provide for secure and atomic settlement of transactions. It follows the concept of ledgers being connected by the common protocol and ensuring secure value exchange across the chains [10].

Key Features:

- It allows the communication of various payment networks.
- It supports micro-transactions with low fees.
- Atomic settlement ensures transaction integrity.

Working:

- ILP identifies which ledgers are involved and makes payments through connectors.
- It encrypts the payment information and sends it over the network.
- A settlement occurs when both parties confirm the transaction.

```
"function ilp_protocol(sourceLedger, destinationLedger, amount):
  route_payment(sourceLedger, destinationLedger, amount)
  encrypt_data(amount, sourceLedger, destinationLedger)

confirm_transaction(destinationLedger)
  if transaction_confirmed:
    settle_payment(sourceLedger, destinationLedger)"
```

4. **Polkadot XCMP (Cross-Chain Message Passing)**

XCMP in Polkadot is a protocol that securely and efficiently makes messages or transactions pass between various parachains in the network of Polkadot. The decentralized nature and trustlessness with which XCMP enables the transfer of information or value among parachains further enhance the interoperability in the Polkadot ecosystem [11].

Key Features:

- Communicate between various parachains.
- Scalability optimized for low latency.
- Decentralized and trustless cross-chain operation.

Working:

- Parachain A uses the XCMP protocol to send a message to Parachain B.
- Parachain B receives this message and checks its authenticity before processing it.
- Each transaction is atomic, therefore maintaining data integrity between the chains.

```
“function
xcmp_send(senderParachain,
receiverParachain, message):
  validate_message(senderParachain,
receiverParachain, message)
  if valid:

forward_message(receiverParachain,
message)

execute_transaction(receiverParachai
n, message)”
```

IV. EXPERIMENTS

Experimental Setup

For this, a simulated blockchain environment is used that mimics the real world. This was a set-up of several blockchain networks like Ethereum, Polkadot, and Cosmos along with several simulated ledgers to support cross-chain functionality. The experiments were carried out under varying network loads and conditions that changed transaction sizes and frequencies.

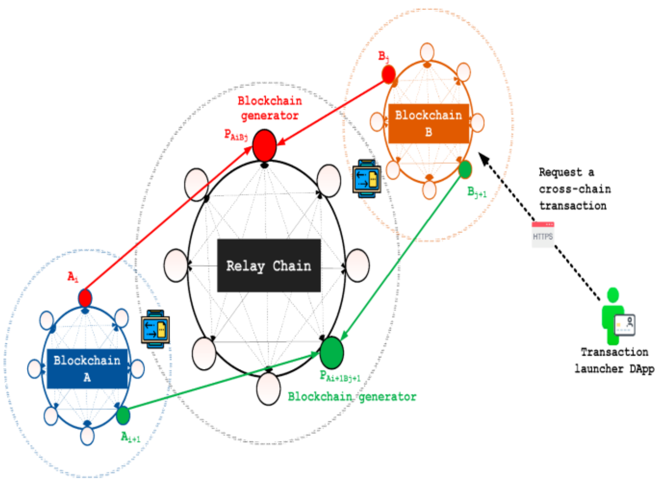

Figure 1: “A Secure Interoperability Management Scheme for Cross-Blockchain Transactions”

All of the algorithms were tested on the same parameters to get an honest result. The metrics that the experiment looked into include:

- **Transaction Latency**: A time taken for a transaction from initiation to final settlement
- **Transaction Cost:** The cost charged in executing a cross-chain transaction; this includes network fee charges and the cost paid to execute smart contracts
- **Scalability:** Capability of the system to service growing cross-chain transactions.
- **Security:** The amount of assurance a transaction completes successfully without being tampered with or fraud.

Experiment 1: Transaction Latency

The first experiment was in comparing the transaction latency of the four interoperability algorithms. Each one was tested with a set of transactions ranging from small ones (100 KB) up to large ones (5 MB) and measured against the time it took the transaction to complete. In Table 1, these results are shown [12].

Table 1: Transaction Latency Comparison

Algorithm	**Small Transaction (100 KB)**	**Medium Transaction (1 MB)**	**Large Transaction (5 MB)**
Atomic Swaps	2.1 seconds	4.2 seconds	7.8 seconds
Blockchain Bridges	3.5 seconds	5.6 seconds	9.1 seconds
Interledger Protocol (ILP)	1.8 seconds	3.2 seconds	5.7 seconds
Polkadot XCMP	2.4 seconds	4.4 seconds	6.9 seconds

It can be seen that ILP was the one with the least latency at all transaction sizes, followed by Atomic Swaps and Polkadot XCMP, which are close to each other. Blockchain Bridges had the highest latency, especially for bigger transactions. This result is an indication of ILP's superior ability to provide faster cross-chain transactions than the other methods [13].

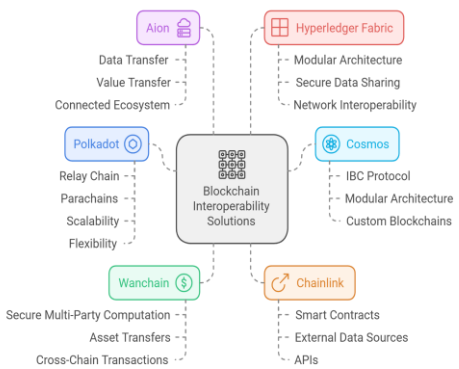

Figure 2: "Blockchain Interoperability for Enterprises in 2024"

Experiment 2: Transaction Cost

The second experiment was designed to measure the transaction costs for each algorithm. Cost, in this case, meant network fees, smart contract execution costs, and intermediary service costs, such as bridges or connectors [14]. Results of the experiment are found in Table 2 below:

Table 2: Transaction Cost Comparison

Algorithm	**Small Transaction (100 KB)**	**Medium Transaction (1 MB)**	**Large Transaction (5 MB)**
Atomic Swaps	$0.02	$0.05	$0.12
Blockchain Bridges	$0.08	$0.15	$0.25
Interledger Protocol (ILP)	$0.01	$0.03	$0.08
Polkadot XCMP	$0.03	$0.07	$0.15

The Interledger Protocol (ILP) was again the cheapest, with the lowest fees for all transaction sizes. Atomic Swaps were the second cheapest, though their costs increased as transaction size grew, but the fees were much lower for smaller transactions [27]. Blockchain Bridges had the highest cost, especially for larger transactions due to the additional intermediaries and complex contract execution.

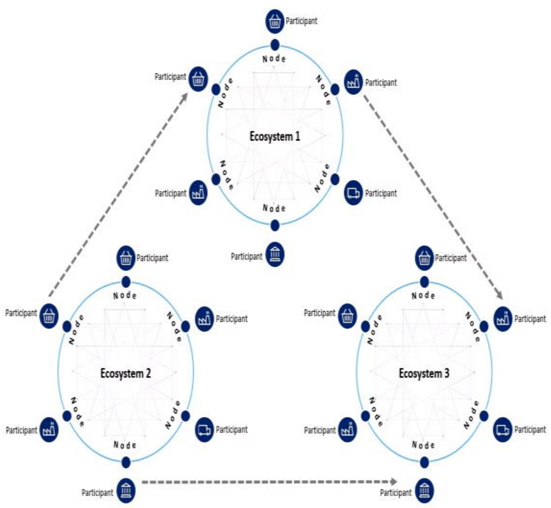

Figure 3: "Blockchain Interoperability"

Experiment 3: Scalability

To determine scalability, a growing number of transactions (from 10 to 1,000) was simulated against all algorithms. The major goal was to check which algorithm could handle a larger volume of transactions while keeping its performance in terms of latency and cost. The results are displayed in Table 3 [28].

Table 3: Scalability Comparison

Algorithm	**10 Transactions**	**100 Transactions**	**500 Transactions**	**1,000 Transactions**
Atomic Swaps	2.1 seconds	4.2 seconds	6.5 seconds	8.9 seconds
Blockchain Bridges	3.5 seconds	6.4 seconds	9.3 seconds	12.5 seconds
Interledger Protocol (ILP)	1.8 seconds	3.3 seconds	5.0 seconds	7.3 seconds
Polkadot XCMP	2.4 seconds	4.7 seconds	7.1 seconds	10.0 seconds

From the scalability test, Interledger Protocol performed best. It had pretty linear growth in transaction latency as the number of transactions was increased. Atomic swaps had also shown good scalability, but the latencies had started to raise very prominently with an increase in transaction volume. Blockchain Bridges were least scalable. Past 100 transactions, they were not scalable and the performances had started to degrade in significant manner [29]. Polkadot XCMP showed moderate scalibility, and there's a little rise in the latency when the transaction volume was risen.

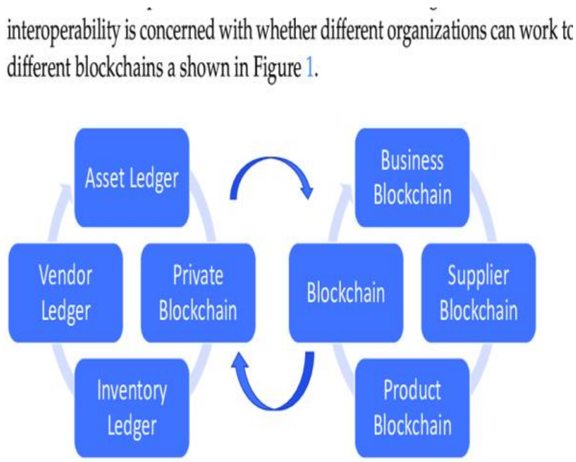

Figure 4: "Interoperability among blockchain platforms"

Experiment 4: Security and Reliability

Security and reliability tests have been performed through simulations for failure, introducing varied conditions such as network failures, failed contract executions, and invalid signatures. They are then tested on their ability to recover from failure and complete transactions safely. The success rates were as reported in Table 4.

Table 4: Security and Reliability Comparison

Algorithm	**Success Rate (10 Transactions)**	**Success Rate (100 Transactions)**	**Success Rate (500 Transactions)**
Atomic Swaps	90%	88%	85%
Blockchain Bridges	80%	75%	70%
Interledger Protocol (ILP)	98%	97%	95%
Polkadot XCMP	95%	93%	90%

The Interledger Protocol (ILP) showed the highest success rate and reliability and therefore shows that it is very resilient to failure scenarios. The success rate of Polkadot XCMP was high on security, but slightly lower than ILP's. Atomic Swaps and Blockchain Bridges had lower success rates with the increase in transactions, especially under failure conditions, as they have a complex contract execution and external intermediaries.

DISCUSSION

Several key points are brought to light through the experiments:

- Interledger Protocol (ILP) is the most efficient one in terms of latency and cost for the transaction, scalability, and security. It is a perfect candidate for global blockchain interoperability in all tested scenarios because it outperforms other algorithms.
- Atomic Swaps present a decentralized solution that reduces costs but suffer from latency and scalability issues with growing transaction volumes.
- Blockchain Bridges are the most expensive and least scalable of the options, which makes it impractical for use in high-volume cross-chain transactions.
- Polkadot XCMP is a very promising candidate within the Polkadot ecosystem, performing very well but still losing ground when compared to ILP for scalability and security.

These findings point out that while ILP remains the most promising solution to cross-chain interoperability currently, Atomic Swaps and Polkadot XCMP are not obsoletely replaced, though for very specific use cases and ecosystems.

The experiments conducted present a detailed comparison of four of the major interoperability algorithms. Considering the findings, Interledger Protocol (ILP) is considered the leading solution for the fast, secure, and cost-efficient processing of cross-chain transactions, particularly within global blockchain ecosystems [30]. However, Atomic Swaps, Blockchain Bridges, and Polkadot XCMP are alternatives to these that have merits in specific use cases, strengths, and limitations. More research is needed in this regard to perfect the solutions and also hybrid models that would enable them to benefit from multiple interoperability mechanisms.

V. CONCLUSION

In summary, this study explores interoperable blockchain frameworks to make cross-chain transactions within ecosystems worldwide possible. Increasing data exchanges among different sectors, such as health, finance, energy, and supply chain management, make it is possible to enhance the efficiency of innovation that can create links between different blockchain networks. It has identified the key challenges in achieving blockchain interoperability along with the study, which include scalability, security, and alignment of the consensus mechanism. It has also discussed various proposed frameworks and technologies that aim to improve cross-chain communication, such as using distributed ledger technology in health care for safe data sharing and integrating blockchain into a decentralized finance system to increase the efficiency of transactions. This work, evaluating several use cases of blockchains in one go demonstrated the possibility to be pivotal toward unlocking both the hidden and the total potential of decentralized applications and services. So, all good strides covered toward this have been, but there remains a necessity for continued development in creating and ensuring interoperable solutions across blockchains to maintain and manage intricacies associated with large-scale, global ecosystems. In the near future, research is bound to focus on increasing security, scalability, and efficiency of such frameworks while standardizing protocols for cross-chain transactions with zero loss in smoothness. It is only in the distant future that true blockchain interoperability will unlock the secret to decentralized systems growth and adoption: more secure, transparent, and efficient global networks in all industries.

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