Cross-Chain Interoperability in blockchain

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***Abstract*—Cross Chain interoperability allows various blockchains to communicate and transfer data and helps in overcoming limitations of isolated blockchains. This enables asset transfer, exchange of data and it allows smart contracts to interact across various platforms. Cross chain interoperability bridges the gap between two different blockchains that have their own protocols and also enhances scalability, flexibility and security. This paper reviews various mechanisms that helps us to achieve interoperability. We will also review challenges that exists while achieving cross chain interoperability and some current available solutions.**

Keywords: Cross-Chain Interoperability, blockchain bridges, relays, atomic swaps, asset transfer

I.INTRODUCTION

We can develop decentralized, secure, and transparent systems with the help of blockchain. But as various new types of blockchains are emerging challenges like isolation, inability of sharing data and asset transfer are also increasing. This lack of connectivity between different blockchains is a main challenge of blockchain.

To overcome this challenge cross chain interoperability plays a very important role. It enables various blockchains to seamlessly communicate with each other, transfer the data and assets across the platforms. This interconnectivity is crucial for applications like decentralized finance Where asset transfer is crucial.

In this review paper, we will review various key mechanisms that enables us to achieve cross-chain interoperability, such as blockchain bridges, sidechains, and interoperability protocols. We will also analyze current solutions that are available in a market , discuss the challenges and limitations that still exists. This paper will give brief overview about cross chain interoperability and it will help us to unlock full potential of blockchain.

A. Understanding Cross-Chain Interoperability

Cross chain interoperability is a ability of various types of blockchains to communicate and transfer the data and assets across platforms. This helps to create a interconnected network of blockchain. Where every individual blockchain can share data with each other and transfer assets.

Cross-chain interoperability mainly aims at improving the scalability, functionality, and flexibility of cross-chain decentralized systems. Interoperability facilitates integration between different blockchain platforms, each one with its own capabilities and advantages, through communication between blockchains. This type of integration is critical for building more advanced decentralized applications that can run across different blockchains.

Overall, the core of blockchain technology is the unlock of the cross-chain interoperability. This allows diverse networks to work together and exchange resources, which results in stronger and more flexible decentralized networks.

B. Key Mechanisms of Cross-Chain Interoperability

1. Blockchain Bridges

Blockchain bridges are protocols that facilitate the connection of two separate blockchains to transfer assets and data between the two. These considerations are in play due to Token Bridges they allows tokens and data to flow between alternate platforms.

Two main types of blockchain bridges exist: trusted and trustless.

Trusted bridges use a centralized entity or a group of entities to move the assets between the blockchains. These entities take care of locking the assets on one blockchain and issuing corresponding tokens on the other. Trustless bridges, on the other hand, utilize

smart contracts and decentralized methods to accomplish the same thing without an intermediary.

2. Sidechains

Sidechains are independent blockchains that run parallel to a main blockchain, allowing assets to move back and forth between the two chains. They can implement different consensus mechanisms, features, and rules, thus adding flexibility and scalability throughout the network. two-way peg is a mechanism that links the sidechain to the main blockchain, allowing assets to be transferred between the two.

Most of the benefits go to the different applications that run on that sidechain, which can cause a certain number of transactions to occur outside of the main blockchain which will eventually decrease congestion while increasing overall scalability. They can also be optimized for use cases such as privacy or high throughput.

3.Relays

Relays are protocols which observe and confirm the state of one blockchain on another. They allow one blockchain to react to events on another blockchain by verifying the validity of transactions and blocks across chains. Such verification is crucial for ensuring data integrity and assuring that cross-chain interactions remain secure and reliable.

Relays are an important component of cross-chain communication and interoperability. Relying on them can help for the confirmation of cross-chain transactions, execute smart contracts over different blockchains, or sharing data between networks. For example, the BTC Relay is a relay based system that enables Ethereum smart contracts to validate Bitcoin transactions.

4. Atomic Swaps

Atomic swaps allow users to trade cryptocurrency from one blockchain for cryptocurrency on another blockchain without third-party involvement. These swaps use a mechanism known as hash time-locked contracts to force both parties to comply with the terms of the swap; if, for example, one party doesn't complete their side of the transaction or provide some guarantee of payment, the reverse transaction will happen automatically.

For the future, atomic swaps are necessary because they allow trustless transactions across the chain with very little counterparty risk. This approach proves invaluable to DEXs and financial applications where trust and safety are paramount. Bitcoin also has atomic swap implementations via the Lightning Network.

5. Interoperability Protocols

Interoperability protocols allow different blockchains to communicate with each other, allowing them to easily exchange data and assets. These protocols establish a uniform way for blockchains to communicate with one another, simplifying the development of interoperable applications.

A good example of such interoperability protocol is the Inter Blockchain Communication (IBC) protocol found in the Cosmos ecosystem. IBC facilitates cross-chain messaging and digital asset transfer, forming an "Internet of Blockchains." A prominent example is the Interledger Protocol which allows cross-chain payments and value transfers between multiple blockchain and even non blockchain networks.

II. CURRENT SOLUTIONS AND TECHNOLOGIES

A. Polkadot

Polkadot provides interoperability between multiple blockchains as a heterogeneous multi-chain framework. It has a central Relay Chain and multiple parachains. Parachains are individual blockchains that process at their own pace in parallel to the Relay Chain and offers a shared secured ability to communicate across chains.

Notably, having this unique structure allows Polkadot to be scalable, since parachains can run concurrently without clogging the network. In addition the message passing system of Polkadot allows for instant communications between the parachains thus making it an important pillar in the cross- chain interoperability narrative.

B. Cosmos

Cosmos is also called "Internet of Blockchains" where each individual blockchain can communicate through the Cosmos Hub using the Inter-Blockchain Communication (IBC) protocol. The Cosmos Hub is like a centralized entity that connects all the zones which helps in sharing data

Tendermint Core consensus engine helps cosmos to provide high performance and security. Cosmos helps developers to build customizable and interoperable blockchains because of its modular architecture thus making it a flexible and scalable solution for cross-chain interoperability.

C. Avalanche

Avalanche is an open-source platform for launching decentralized applications and enterprise blockchain deployments in one interoperable, highly scalable ecosystem. Its unique consensus mechanism that leverages a probabilistic approach, results in high throughput and low-latency of the network, thereby paving way for a plethora of decentralized applications.

Avalanche subnets are customizable for different applications, and they are interoperable with each other and the main network, offering flexibility to the platform. By making sure Avalanche supports the Ethereum Virtual Machine (EVM), developers can deploy EVM-compatible smart contracts, expanding the interoperability capabilities even further.

D. Chainlink

Chainlink allows smart contracts to connect to real-world data, events, and payment methods. Cross-Chain Interoperability Protocol (CCIP), an integral part of it, lies at the heart of secure and universal cross-chain communication.

The oracles of Chainlink are highly extensible and are capable of supporting a wide range of data sources with various different blockchain networks. By providing data feeds Chainlink is a best example which supports the ecosystem and enables cross chain communication, etc.

III. USE CASES AND APPLICATIONS

A. Asset Transfers

Cross-chain interoperability refers to the ability to move assets freely over different digital platforms, whether they be different blockchains or separate financial systems. This feature is especially useful for users who need to move assets across various blockchain networks without having to depend on centralized exchanges. Interoperability enhances liquidity and increases the usability of digital assets by allowing them to be used across multiple platforms.

These bridges may be used by users, for example users could do token transfers from Ethereum to Binance Smart Chain and therefore use DeFi applications on both networks. Another approach to improving the efficiency and flexibility of the blockchain ecosystem is seamless interoperability between different chains.

B. Decentralized Finance (DeFi)

Because of ability of DeFi protocols to incorporate assets and services from various blockchains, the cross-chain interoperability has been proven a big advantage to the DeFi ecosystem. It also leads to an integrated financial system enabling users to use more financial products and services.

Moreover, cross-chain interoperability leads to the development of DEXs that provide trading pairs across multiple blockchains. This similarly enables DeFi platforms to provide lending and borrowing products based upon assets on various networks, subsequently diversifying and expanding DApps availability over the marketplace.

C. Data Sharing

All while achieving scalability by executing a scalable subset of state transitions on different chains and by enabling secure cross-chain communication; unlocking many new use cases (e.g. supply chain management, healthcare record collaboration or identity verification). Interoperability has created a pathway for the movement of data and assets across blockchains.

This facilitates the movement of different types of data between separate chains. In parallel, greater visibility is enabling increased traceability and trust throughout the supply chain, and so reducing the risk of fraud and

ensuring product authenticity.

D. Cross-Chain Smart Contracts

They unite multiple blockchains with interability for some complex operations and advanced decentralized applications called Cross-chain smart contracts. These smart contracts can communicate between different networks, allowing for greater functionality and for making transactions and triggering events and managing data.

IV. CHALLENGES AND LIMITATIONS

A. Security Risks

security remains a big challenge with cross-chain interoperability, especially for blockchain bridges or different mechanisms to make cross-chain connections work. Homogeneity between blockchains within a multichain ecosystem opens up avenues for attackers to exploit vulnerabilities in one Dapp's code to meddle in any Dapp's cross-chain transfers with potential asset losses.

These security vulnerabilities have resulted in the loss of millions of dollars worth of assets in several high-profile blockchain bridge security breaches. To prevent this, strong security protocols, like multi-signature systems, decentralized validation and stringent auditing are necessary.

B. Scalability Issues

Cross-chain communication introduces another barrier to cross chain interoperability, i.e. scalability. But as many users use multiple blockchains, ensuring efficient and reliable processing of high transaction volumes is a must, requiring consensus mechanisms and optimized protocols.

Therefore, through multiple commonly used blockchains, we provide space for concurrent inter-chain transactions, thereby increasing the comparison of cross-chain transactions with a large single-path congestion. But finally, to fix this interoperability issue it requires scalability solutions like sharding and layer 2 protocols and different low-latency consensus algorithms to keep interoperability systems as performant and as speedy as possible.

C. Complexity and Usability

Cross-chain interoperability solutions are also technically complex to implement and maintain, which can be overwhelming for developers and users trying to work with these systems. Besides, cross-chain interactions are proved to be a complex trust model which has great adverse effect on user adoption.

Overcoming this challenge requires building user-friendly interfaces and tools to streamline cross-chain processes. They just need clear, well-designed tools that guide and help them interact with the different blockchains to enjoy the interoperability benefits.

D. Standardization

The issues of standardization and unified protocols of various chains, which leads to fragmentation in the defined blockchain level ecosystems. As a result, there are no universal standards for blockchain protocols, resulting in seamless and consistent interoperability across all blockchain networks.

These systems will have to seamlessly interact with one another, which acts as a level forming bridge connecting them all together. By creating standardized protocols, the blockchain community can create a more inclusive and interoperable ecosystem through a new system of interconnected fabrics.

V. IMPLEMENTATION

We have implemented cross chain interoperability through two ways

Method 1:- Through Alchemy and Javascript code

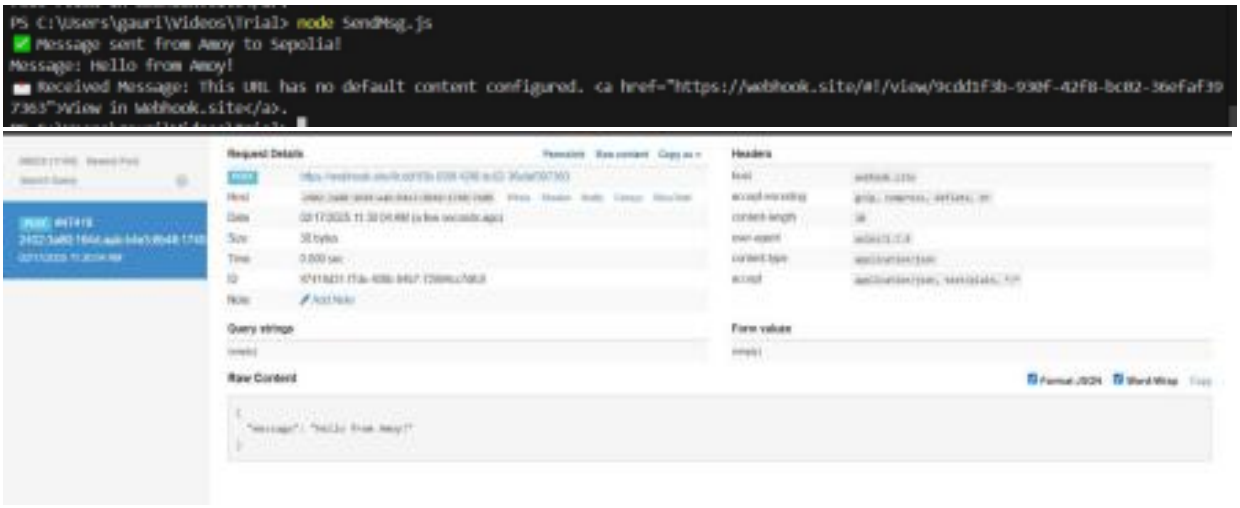
Step 1:- Create account in Alchemy
Step 2:- Create two Apps one for Ethereum Sepolia and one for Polygon Amoy and copy API Key

Step 3:- Go to https://webhook.site/ and copy your unique url(You can view your messages here)
Step 4:- install node.js and execute following javascript code

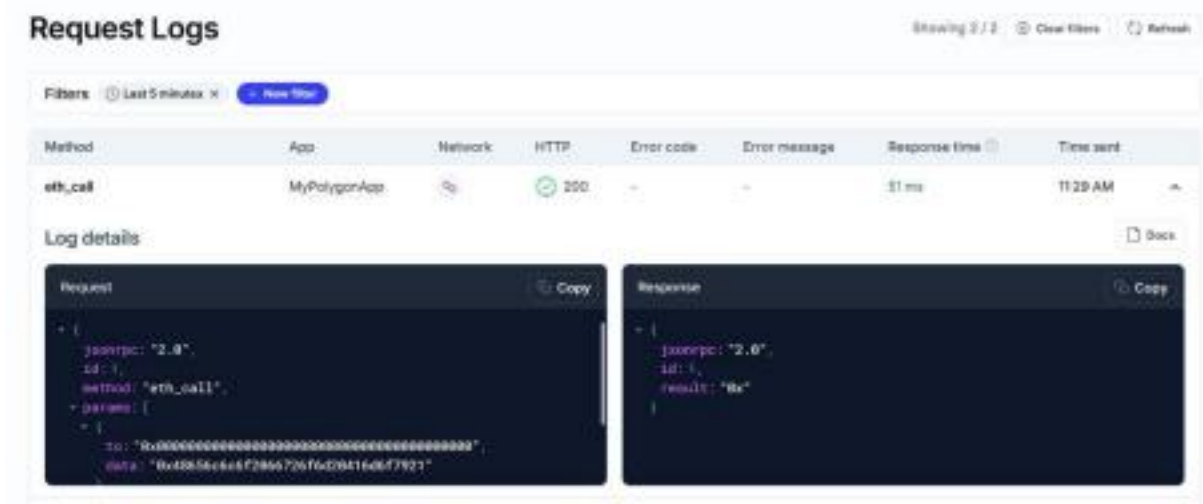
CODE:-

```
//Sending message from Polygon Amoy to Ethereum Sepolia

const axios = require("axios");
const AMOY_API_KEY = "nupb6uy9HhQr5f6gf-nTfKmWcI2yzitE";
const WEBHOOK_URL = "https://webhook.site/9cdd1f3b-930f-42f8-bc02-36efaf397363"; const AMOY_URL =
`https://polygon-amoy.g.alchemy.com/v2/${AMOY_API_KEY}`;

async function sendMessage(url, message) {
  try {
    const messageHex = "0x" + Buffer.from(message, "utf8").toString("hex"); const response = await axios.post(url,
    {
     jsonrpc: "2.0",
     id: 1,
     method: "eth_call",
     params: [
       {
        to: "0x0000000000000000000000000000000000000000", // Dummy address data: messageHex,
       },
       "latest",
     ],
    });
    console.log("Message sent from Amoy to Sepolia!");
    console.log("Message:", message);
  } catch (error) {
    console.error("Errorstoring message:", error.response?.data || error.message); }
}

async function receiveMessage() {
  try {
    const response = await axios.post(WEBHOOK_URL, {
      message: "Hello from Amoy!", // Send a message back or relevant data
    });
    console.log("Received Message:", response.data);
  } catch (error) {
    console.error("Error receiving message:", error.message);
  }
}
sendMessage(AMOY_URL, "Hello from Amoy!");
setTimeout(() => receiveMessage(), 5000);
```

Output

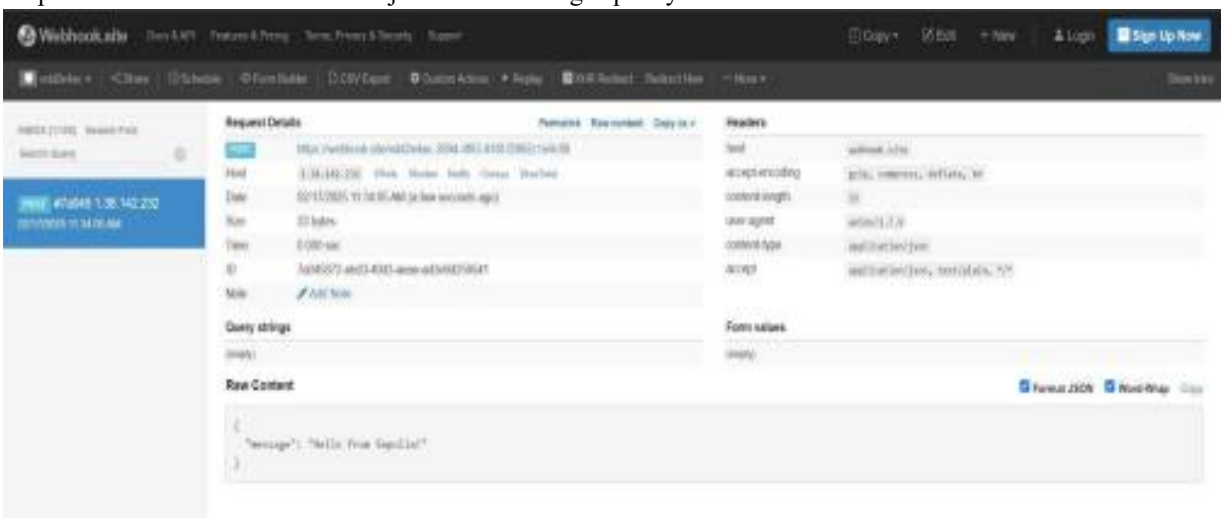


You can see request isinitiated in Request logsfrom Polygon Amoy app that we created in Alchemy



//Sending message from Ethereum Sepolia to Polygon Amoy

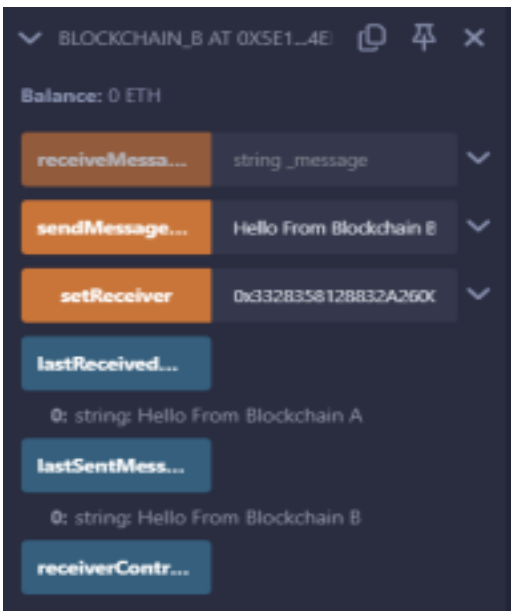
Steps and code will be almost same just need to change api key and webhook url

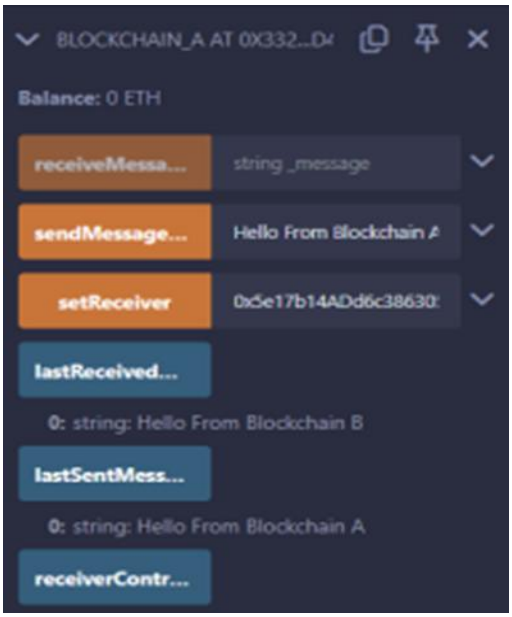


Method 2:- Through Remix IDE and Smart contracts
Steps 1:- create two smart contracts in Remix IDE . one for blockchain A and another for Blockchain B Steps 2:- Deploy both contracts. Now You can send and receive messages acrossthese two blockchains.

```
// SPDX-License-Identifier: GPL-3.0
pragma solidity >=0.8.2 <0.9.0;
interface BlockchainB {
function receiveMessageFromA(string memory _message) external;
}
contract BlockchainA {
string public lastSentMessage;
string public lastReceivedMessage;
address public receiverContract;
event MessageSent(string message);
event MessageReceived(string message);

function setReceiver(address _receiver) public {
receiverContract = _receiver;
}
function sendMessageToB(string memory _message) public {
lastSentMessage = _message;
emit MessageSent(_message);
require(receiverContract != address(0), "Receiver contract not set");
IBlockchainB(receiverContract).receiveMessageFromA(_message);
}
function receiveMessageFromB(string memory _message) external {
lastReceivedMessage = _message;
emit MessageReceived(_message);
}
}
```

The code will be same for blockchain B as well.





VI. CONCLUSION

To summarize, cross-chain interoperability is crucial for the expansion and unification of blockchain networks, allowing seamless communication and sharing of assets, data, and functionalities. Although blockchain bridges, sidechains, and interoperability protocols are promising solutions, security risks, scalability, and standardization issues remain concerns. These interoperability solutions will pave the way for a future with even more blockchain systems, and will be the backbone of a more decentralized, interconnected, and connected world

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