A Conceptual Insight Into Achieving Interoperability Between Heterogeneous Blockchain Enabled Interconnected Smart Microgrids

Disha Lagadamane Dinesha
Department of Management Studies
Indian Institute of Science
Bengaluru , India
dishad@iisc.ac.in

Balachandra Patil
Department of Management Studies
Indian Institute of Science
Bengaluru , India
patilb@iisc.ac.in

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***Abstract*—Blockchain technology (BCT) has emerged as a game-changer for many industries since its inception in 2008. Its application in the energy industry as blockchain enabled interconnected smart microgrids (BSMG) is on the rise as it can execute energy trading, automate the market operations, manage the grid, and facilitate real-time payments. With the increase in usage of BSMGs, different types of BCT will emerge, making the system heterogeneous in nature. BCT is also limited currently due to its scalability and low transaction rate. Interoperability between heterogeneous BSMGs can counteract the drawbacks and improve the functionality and, thereby, adoption of BCT in energy. This paper recognises the need for interoperability and thoroughly reviews the different methods of interoperability that currently exist (i.e., notary mechanism, relay or side chains, hashed time-locked contracts, and blockchain routers). Two relay mechanisms - Polkadot and Cosmos with Inter Blockchain Communication Protocol (IBC) are reviewed further to determine the usability of the protocols. Finally, a conceptual architecture of interconnection of heterogeneous BSMGs is proposed. Conceptual solution to connecting Ethereum and Hyperledger Fabric to the Cosmos Hub through IBC is explored. While interoperability between heterogeneous users is addressed in Decentralized Finance (DeFi), it has not yet been addressed in energy. A conceptual solution is provided for this research gap for the first time in energy domain.**

***Index Terms*—Blockchain Enabled Smart Microgrids (BSMG), Interoperability, Inter Blockchain Communication Protocol (IBC), Energy Internet, Heterogeneous Blockchains**

I. Introduction

Blockchain technology (BCT) has found applications in many industries like finance, healthcare, supply chain, energy, and internet of things (IoT). Many projects globally are investigating the applications of BCT in the energy industry which range from automating microgrids to executing trade of energy units. These projects are set up on different BCT platforms with different consensus mechanisms [1]. This leads to a variety or heterogeneity amongst Blockchain Enabled Smart Microgrids (BSMG) [2]. It is tackled in Blockchain 3.0 as it focuses on cybersecurity, improving performance, cost-effectiveness, enhancing scalability, and incorporating interoperability. However, since BCT is still in the early stages of development, it has few drawbacks too. Scalability is one such limitation as BCT projects can not handle as many transactions per second (or throughput) as UPI or Visa transactions. Inter-chain or inter-platform communications and transactions are also not easy due to lack of standardisation, regulation, and required infrastructure. Interoperability between the different BCT platforms is viewed as a solution to these problems. With the advent of Blockchain 3.0, interoperability between heterogeneous blockchains without compromising on data security and blockchain sovereignty seems to be a possibility [3].

The importance of interoperability is discussed in detail in [4]. To summarise, the system must be made scalable to handle the real-time transactions which will increase in the future due to increasing adoption of BCT [5]. Soon, heterogeneity in BCT platforms will also emerge. While two homogeneous blockchains are easily interoperable due to their technical similarities (like consensus mechanism and block formation), heterogeneous blockchains are not as they are technologically different. Thus, interoperability protocols and methods for heterogeneous blockchains need to be explored to ensure secure data and asset transfers. It will also establish trust and communication between the different systems (public, private, permissioned or permissionless). This will prevent one type of blockchain from monopolising the industry and ensure equity among all participants. Hence, interoperability will help the systems to achieve true decentralisation and freedom from central authority and third parties, as it was originally designed to. Lastly, several market models involving inter microgrid transactions have emerged over the years which still need to be tested and applied to BSMGs. Establishing an interoperable framework will give research in this direction an impetus and allow for the practical implementation of such market models in TES or BSMG systems. Additionally, BCT is still in developing stages due to which there is no consistent standardisation between the different platforms and mechanisms.

Inter-chain transactions are explored in DeFi in order to promulgate the adoption of BCT into the mainstream finance and disrupt the existing, traditional methods. Sovryn is a DeFi protocol which is built on Ethereum and deployed on Bitcoin sidechain [6]. It can be used on other blockchain networks as well and expands the Bitcoin system by connecting it to smart contracts and Web3-based wallets. Fusion is another interoperable system built for DeFi. It built Distributed Control Rights Management (DCRM) which uses a decentralized custodian model along with cryptography techniques for key generation and transaction signing to address cross-chain transactions [7]. Osmosis is an Automated Market Maker (AMM) built with Cosmos SDK which facilitates decentralized exchange between blockchains connected to the Cosmos hub [8]. While interoperability has been discussed and implemented in DeFi, the energy sector is yet to discuss and implement it. The current paper recognises the need for interoperability between heterogeneous BSMGs and tries to provide a conceptual solution. This paper reviews the various methods of interoperability adopted by BCT till date. It also envisions an interconnected BSMG setup along with detailed discussion on the architecture and conceptual implementation of InterBlockchain Communication Protocol on various cases.

II. Interoperability : State of the Art

As per [1] which reviewed 140 BCT projects in energy, around 60% of the projects are built on Ethereum and its derivatives, 11% on Hyperledger, and 7% on Tendermint. This study reveals the diversity of options available to the participants, showing the need to develop methods for interoperability. This involves converting the value of an asset stored originally on one chain to the value of the asset on the other chain which is designated to be the destination chain without the loss or gain of value [9]. Another challenge is to verify the transaction status in a trustless environment. It is difficult for one chain to confirm and validate the transactions occurring on another chain. Thus, any method of blockchain interoperability must satisfy the following criteria as per [10]. It should support the different types of blockchain platforms while not modifying the existing technology by means which require forking or modifications to smart contracts whenever a new inter-blockchain link is added. The operation should be free of interference from end users. It must not interfere with the performance or security of the other participating blockchains. Lastly, its dependence on off-chain infrastructure and systems must be as minimal as possible. The methods discussed here adhere to the criteria presented above.

A. Methods of Interoperability

Usually, third party assistance is needed for heterogeneous chains [9]. Interoperability between heterogeneous chains is conceptualised in this paper as it poses challenges that need to be addressed, unlike with homogeneous chains. The methods of interoperability can be broadly classified into 4 types - Hash-Locking, Notary Mechanisms, Relay/Side Chains, and Blockchain Routers.

1) Notary Mechanisms : Notary mechanism is the simplest of all schemes [11]. An entity or a set of entities is trusted to act as intermediary which claims to chain B that a claim by chain A (say, an event occurring on chain A) is true. Notaries need to have accounts to facilitate the cross-chain transactions and actively listen to the events taking place on the other chain in order to act automatically based on trigger event [9]. It can be of 3 types - single signature notary mechanism (where a node acts as a notary), multi signature notary mechanism (where multiple nodes act as a notary entity), and distributed signature notary mechanism (where multiple notaries which hold the key are divided and distributed among the notaries in a random manner) [9]. While the first type is very efficient in terms of operation and processing, it is more vulnerable to attacks. Hence, the latter 2 types are more robust as they weaken the risk of single point of failure which the first type is more susceptible to.

Interledger Protocol (ILP) by Ripple uses escrows or connectors to stage the transfers and commit the cross-chain transactions upon receiving a cryptographically signed proof of meeting certain preconditions [12]. Notary is used in the atomic transfer mode (where there is a guarantee that either all the components of the transfer will be executed or all components will be aborted) [13]. It uses a BFT consensus mechanism with ad-hoc group of notaries to synchronise the execution of all the components of the required transfer. Corda by R3 also uses notaries to record transactions and consensus data [14], [15].

2) Relay/Side Chains : A side chain is a chain which can verify the data of the other blockchain [9]. It is also called a relay or a federated pegged side chain [11]. It facilitates moving of assets across chains through a multisig scheme. Bidirectional pegging side chain has also been developed which allows for two-way movement of assets [9]. This can be achieved in 4 ways - single hosting mode (simplest way where the participating chains send their assets to a custodian like in the single notary mechanism and the custodian sends the corresponding capital to the side chain), joint pegging mode (uses union of notaries as asset custodian along with multiple signatures to increase security), drive chain mode (transaction processing node executes fund hosting, submits asset locking data to the other chain, initiates proposal, and unlocks the specified asset to the destination chain), and simple payment verification (SPV) pegging mode (a light client on one chain can verify the existence of the corresponding transaction).

Elements platform employed this mechanism to design the first successful federated pegged side chain for Bitcoin [16]. This framework is also used in Liquid which is a Bitcoin backed side chain created by Blockstream [11]. Plasma is a side chain developed for Ethereum where each side chain is created with its own set of rules which are governed by a smart contract created on Ethereum [16], [17]. BTCRelay is a smart contract on Ethereum that provides unidirectional operability by reading the Bitcoin chain [11]. Polkadot is a sharded blockchain which unites heterogeneous chains called parachains which are connected to the Polkadot Relay Chain [18]. It also has a third component called Bridges with which it connects to the external networks like Ethereum and Bitcoin too [18], [19]. The appXchain is an Ethereum-based smart contract developed to allow heterogeneous chains of any architecture type to communicate, share, and request for data in the healthcare industry [10].

3) Hashed Time-Locked Contracts (HTLC) : HTLCs are smart contracts which use hash-locking and time-locking techniques to lock transactions and ensure that they are either executed or cancelled after a timeout to prevent counterparty risks [16]. It achieves cross-chain atomic operations without knowing much about the other chain [11]. The Bitcoin Lightning Network is one of the first projects to adopt HTLC [20]. Instead of a bidirectional payment channel, HTLC is used to construct a network of channels incorporating multiple hops to reach the intended destination chain. This ensures high volume, low latency payments. TierNolan proposed hash-locked atomic swap of assets to ensure security and to execute the transactions without the presence of third parties [9]. ILP also uses the concept of time-locking. The atomic mode of payment uses notary system while the universal mode of payment uses bounded execution time windows which eliminates the need for external cooperation [13]. The advantage of using this method is that it provides security to all the non-faulty participants which are connected only to the non-faulty chains, assuming there is bounded synchrony with a known bound.

4) Blockchain Routers : In this method, certain designated blockchain nodes act as routers which transmit requests between the participant chains [19]. This involves changing the architecture of the node so that it acts as a router [16]. The concept is defined in [21], and is inspired by internet's routing architecture. The architecture consists of validators (most important participants which verify and forward the block to the correct destination), nominators (it is rewarded or punished based on the performance of the validator it supports and has no other function in the system), connectors (only data source for validators), and surveillants (monitors the blockchain router's behaviour). A cross-chain model using blockchain routing involving multiple blockchains is implemented and investigated in [22]. A three phase commit is used to confirm the communication result while escrow transfer is used to eliminate third party involvement during transactions. This model accelerates transactions and increases the throughput of the blockchain. Based on the router concept, an algorithm called Multicast Routing Tree (MRT) is presented in [23]. It is a real-time multicast routing algorithm which has a high degree of resource sharing along with the assurance that a routing solution can be found in all the eligible cases.

B. Inter-Blockchain Communication (IBC) Protocol

It is difficult to create cross-chain bridges because blockchains are designed to operate in trustless environments. So, it is difficult for them to trust data that is outside the blockchain. Inter-chain exchanges are complex, especially when the chains are heterogeneous in nature, as data verification requires extensive computational proof before being accepted. Some solutions to address the challenge of interoperability have been proposed. Polkadot is a shared protocol that facilitates seamless operation of blockchain networks. It allows for token and data exchanges through the use of parachains and parathreads which connect to Polkadot Relay Chain [24]. It enables transfer across open, public, permissionless, and private, permissioned blockchains via bridges. Polkadot uses XCM, a standard format, which allows for secure data transfers across parachains and bridges. Ethereum 2.0 allows for cross-shard communication where transactions on one shard can trigger events on another [25]. These are top-down approaches which are simple and predictable. Yet, they face technical difficulties as it is hard to assure validation of state transactions, for all shards to adhere to single validator set, to upgrade over time, and to manage its brittleness [26].

Cosmos is another open-source project which aims at blockchain interoperability [27]. It consists of Cosmos SDK, Inter Blockchain Communication (IBC) Go, and Tendermint Core. It contains a Hub which is the central chain and several Zones which are blockchains that are connected to the Hub. All the blockchains connected to the Hub are interoperable via IBC which facilitates inter-zonal communication and transactions [28]. IBC is a bottom-up approach (similar to TCP/IP internet protocol for computer networks) which enables cross-chain communication by specifying the set of requirements, functions, and properties [26]. Most importantly, IBC is flexible with the 3 major BCT platforms - Ethereum (which when used with the Tendermint consensus mechanism becomes Evmos), Hyperledger Fabric, and Cosmos/Tendermint. It can also be implemented on top of any other BCT framework and in stand-alone ledgers (such as Substrate on which Polkadot's SDK operates) as well [26] which is currently not available in other solutions. IBC is now extensively used in DeFi as discussed earlier. Ambitious projects like Cosmos and Osmosis utilise IBC for critical financial and asset exchanges [8], [27]. Many digital wallets like Metamask and Keplr are IBC enabled, making it easy to connect to a wallet and transfer tokens [29], [30]. Due to these advantages, IBC is assessed to be the best-fit solution for the research problem and is chosen as the interoperability mechanism for this paper.

C. Related Work in Energy Sector

In [31], cross-chain communication has been employed to facilitate energy transactions between the various energy sub-chains. Different energy sources are assigned respective blockchains which transact with each other through a relay chain which uses an improved Boneh-Lynn-Shacham signature scheme consensus algorithm based on PoS and BFT. In [32], a privacy preserving cross-chain payment scheme is proposed. An optimised version of HTLC is used to lock the trading asset and non-interactive zero-knowledge (NIZK) is used to establish credibility of the HTLC process. The simulation is tested on Ethereum Rinkeby test network and the blockchains (Ethereum) are simulated using Ganache. Both studies involve transactions between homogeneous chains networked on the same BCT platform. Since complete interoperability involves transactions between heterogeneous chains too, this research problem has not been sufficiently explored and is currently a research gap as identified in [2], [5]. The challenges regarding scalability and interoperability are mentioned in [5] while a conceptual discussion is conducted in [2]. The latter proposes executing interactions between Ethereum, Hyperledger and Tendermint platforms through IBC, but does not discuss the required setup or the practical implementation. Data exchange (buy and sell calls for energy units) between two BSMGs connected via IBC is explored in [4]. A decentralized token exchange for BSMGs which facilitates exchange and interconversion of energy tokens and digital currencies is proposed and implemented in [33]. However, this too is limited to chains connected to the Cosmos Hub through IBC. While Ethereum and Hyperledger can be connected to the Cosmos Hub, the operational details have not been explored till now. They require additional processes to connect to the Cosmos Hub and become completely interoperable through IBC. Thus, interoperability studies in energy domain are limited to homogeneous or same BCT platforms and need to be extended to heterogeneous platforms too as proposed in this paper.

III. Conceptual Architecture

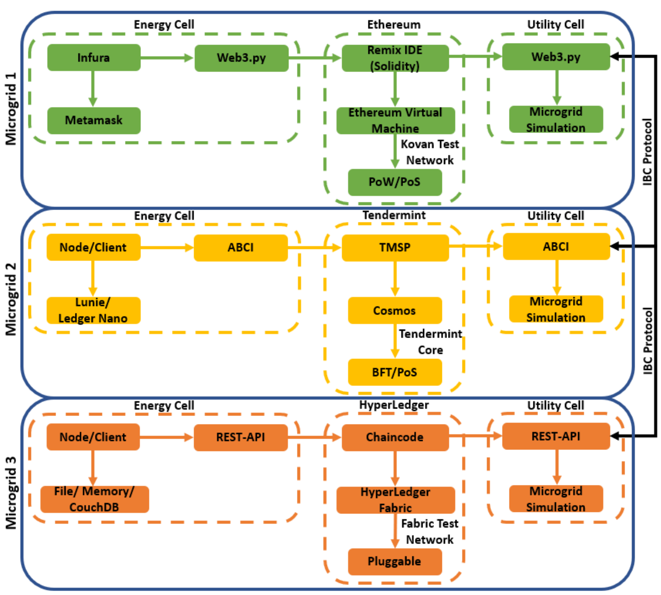

Fig. 1: Proposed Inter-Microgrid Setup as Given in [2]

In this section, the conceptual architecture for interoperability between different types of blockchains is discussed. Since Ethereum, HyperLedger, and Tendermint are the most popularly used blockchain platforms [1], they have been discussed here. Fig 1 depicts a hypothetical BSMG setup interconnected through IBC as referenced from [2]. Micrograms 1, 2, and 3 are set up on Ethereum, Tendermint and HyperLedger Fabric platforms, respectively. The setup also contains the consensus mechanisms (PoW, PoS, BFT), interface mechanisms (Web3, ABCI, REST), digital wallets (Metamask, Keplr, Lunie), and smart contracts (Solidity/TMSP/Chaincode) which execute the market agreement. IBC can be used to link either 2 BSMGs, a BSMG and an individual user, or 2 users involved in P2P transactions. To simplify, a test system of 2 microgrids consisting of 2 users each is used as referenced from [4]. Microgrid 1 uses the ledger called Blockchain 1 while Microgrid 2 uses Blockchain 2. The following sections depict how Ethereum and Hyperledger Fabric can be connected to the Cosmos Hub.

A. Connecting Cosmos-Evmos Chains

The Ethereum Virtual Machine (EVM) is a software environment that runs on the Ethereum. It has a vast network of tools like Ganache, Solidity, Truffle, etc. In order to make it compatible with Cosmos/Tendermint, EVM is built on the Cosmos SDK. This is called Evmos and it serves as a bridge between Ethereum and Cosmos [34]. Since it is connected to the Cosmos Hub, it can now interact with other similarly connected blockchains. The basic block diagram of this setup is shown in Fig 2. Microgrids 1 and 2 operate on Blockchain 1 (set up on Cosmos) and Blockchain 2 (set up on Evmos), respectively. The blockchain consists of modules which are IBC enabled, i.e. one can connect two modules by establishing an IBC channel through a relayer between them. While the Evmos daemon is set up using its CLI tool (evmosd), Cosmos Daemon is set up using Gaia CLI tool (gaiad) which enables the user to interact with the Cosmos Hub [35]. An IBC relayer can be used to connect the two channels. An appropriate relayer can be chosen from this list [36].

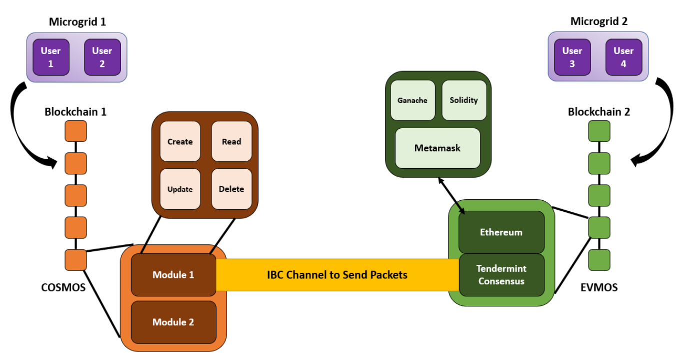

Fig. 2: Block Diagram of Components in Cosmos-Evmos Connection

B. Connecting Hyperledger Fabric-Cosmos Chains

Fabric-IBC allows Hyperledger Fabric to interact with other BCT without the involvement of a third party [37]. Its module can be used with Chaincode and Cosmos modules to enable an IBC connection between Fabric and Cosmos. While Fabric-IBC focuses solely on sending and receiving IBC packets and adhering to the InterChain Standards (ICS) specifications, it can accommodate new functions like security and privacy of the data within the packet [37]. A Hermes relayer (which is an open-source IBC relayer implemented in Rust [38]) can be used to connect the two blockchains as shown in Fig 3. Gaiad manager (a CLI tool) is used to install and configure Hermes relayer.

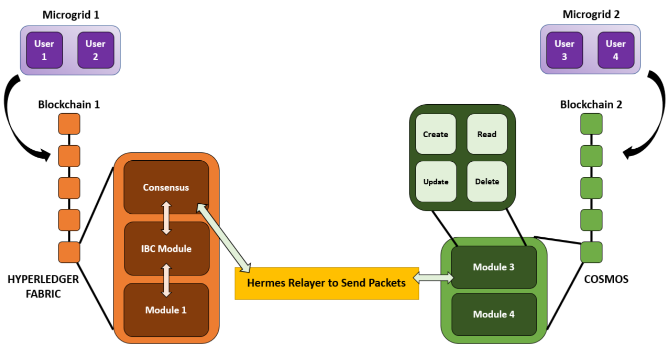

Fig. 3: Block Diagram of Components in Fabric-IBC

IV. Conclusion

BCT is disrupting various industries, including the energy industry. Due to the increasing demand for blockchain enabled interconnected smart microgrids (BSMGs), there is an increase in the need for scalability and interoperability. It is essential to incorporate interoperability in order to connect heterogeneous BSMGs and prevent the monopolisation of any one BCT. The different methods of interoperability are reviewed in detail in this paper. A conceptual architecture is also presented along with the methods to connect Ethereum and Hyperledger to the Cosmos Hub. Future work will entail the implementation of the proposed concepts.

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