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SURVEY

Unlocking the Potential of Interconnected Blockchains: A Comprehensive Study of Cosmos Blockchain Interoperability

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ABSTRACT The Cosmos blockchain is a decentralized network of independent blockchains that addresses scalability and interoperability difficulties in blockchain architecture. Through the use of the Tendermint consensus mechanism and the Inter-Blockchain Communication (IBC) protocol, the Cosmos blockchain enables transactions that are both safe and smooth across a variety of blockchain platforms. One of the most important aspects of its design is the Atom token, which is responsible for ensuring the safety and governance of the network and, as a result, improving interactions across different chains. This comprehensive study covers various topics, including analyzing the techniques that facilitate communication between different blockchain systems. Exploring the subtleties of Cosmos blockchain' architecture and assessing the usefulness and efficiency of the system through a review of transaction data and Atom token volume in the cryptocurrency market. The results contribute to the discussion on blockchain interconnectivity by highlighting the Cosmos blockchain's potential to revolutionize engagement with distributed ledger technologies. The study also emphasizes the Cosmos blockchain's strategic importance in developing blockchain ecosystems and their impact on digital commerce and governance.

INDEX TERMS Blockchain, validators, ledgers, interoperability, cross-chains, inter-chain communication, internet of chains, tendermint, cosmos blockchain.

I. INTRODUCTION

The landscape for blockchain is an ever-evolving region with innovations happening in real-time. Several solutions are being created to cater to specific challenges faced by blockchain. Where a chain is particularly focused on a singleton application, improving its performance and maintaining its components is a separate task in itself [1]. A step further on this, one of the key areas that today's businesses and developers are actively trying to unravel is how different blockchains can interact and pass information from one kind of data domain to another [2], [3]. This is a challenging area regarding blockchain since the entire concept of the ledger was to limit how data can be altered as little as possible. Therefore, this pursuit of interconnectivity presents an interesting problem to solve. With its unique features, the Cosmos blockchain [4] stands at the forefront of this endeavor. This research paper aims to explore the intricacies of the Cosmos blockchain's interoperability, examining its main features, architectural design, and role in addressing the pressing need for an inter-operable blockchain ecosystem, commonly referred to as an inter-chain [5]. Byzantine Fault Tolerant (BFT) consensus algorithm [6] to its innovative Inter-Blockchain Communication (IBC) protocol, we will

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TABLE 1. List of common acronyms and descriptions used in the paper.

Abbreviation	Term
ABCI	Application Blockchain Interface
AIC	AION Interchain Communication
AION	Alliance of Interoperable Networks
ANN	Artificial Neural Network
ANNChain	Artificial Neural Network Chain
Agri-SCM-BIoT	Agriculture Supply Chain Management using Blockchain and the Internet of Things
BFT	Byzantine Fault Tolerance
BTP	Blockchain Transmission Protocol
CBDC	Central Banking Digital Currency
CI/CD	Continuous Integration/Continuous Deployment
DDoS	Distributed Denial-of-Service
DeFi	Decentralized Finance
DApps	Decentralized Applications
DoS	Denial of Service
DSA	Double-Spend Attack
EOS	Electro-Optical System
FPA	Fake Proof Attack
IBC	Inter-Blockchain Communication
ICON	Interconnected Network
ICS-23	Interchain Standard-23
ILP	Interledger Protocol
LFT	Loop Fault Tolerance
MFA	Multi-Factor Authentication
MTN	Masternode Token Network
NPoS	Nominated Proof-of-Stake
PAM	Proof of Absence Manipulation
PBFT	Practical Byzantine Fault Tolerance
PoA	Proof of Authority
PoET	Proof of Elapsed Time
PoW	Proof of Work
RSK	Rootstock Blockchain
SCP	Stellar Consensus Protocol
SDK	Software Development Kit
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TPS	Transaction Per Second
TV	Television
WWW	World Wide Web
XCMP	Cross-Chain Message Passing

explore how Cosmos blockchain has engineered a robust foundation for interconnectivity. To assist in reading, we have included a list of acronyms used throughout this paper in Table 1.

One of the earliest proposals for inter-blockchain communication was made by Jae Kwon in 2014, who introduced the concept of Cosmos blockchain, an "Internet of Blockchains" that would allow heterogeneous chains to interoperate using a hub-and-spoke model [4]. The Inter-Blockchain Communication Protocol (IBC) was later developed as an open-source protocol for relaying messages between separate distributed ledgers, which could support a variety of network topologies and applications [7]. IBC was launched in March 2021, enabled on 22 networks as of November 2021, and reached 107 networks by the end of 2023 with more than 2 million monthly active users [8]. With this expanding landscape, the need for interoperability becomes increasingly apparent. The second section of our analysis will explore the fundamental requirement for an interoperable blockchain, shedding light on the challenges posed by isolated networks and the potential benefits a well-connected blockchain ecosystem can bring. To better understand the inner workings of the Cosmos blockchain, the next section of this paper will conduct a thorough review of its architecture. Figure 1 shows various

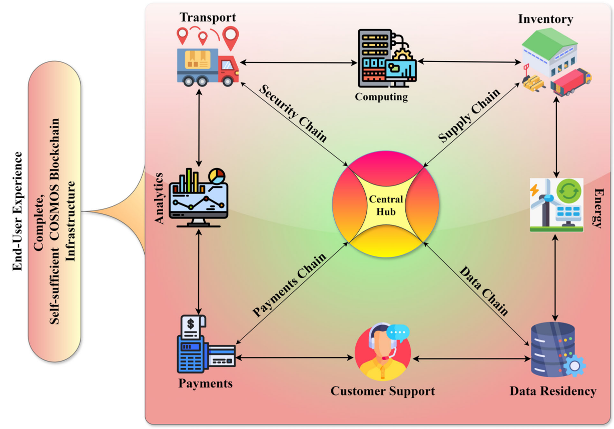

FIGURE 1. Infrastructure of interoperable Cosmos blockchain.

Cosmos blockchain-based infrastructures connecting key operational areas such as transport, inventory, energy, and customer support through a central hub. It integrates security, payments, data, and analytics chains to provide a self-sufficient, decentralized ecosystem for enhanced efficiency and user experience. We can see how a business enterprise can utilize an interoperable blockchain network to unify its infrastructure into a single customer experience. The main advantage is that all the to-and-from communication is secured and encrypted end-to-end inside one self-reliant ecosystem. From the hub-and-zone model to the mechanisms facilitating communication between independent blockchains, this section will unveil the intricacies that make the Cosmos blockchain a standout solution in the pursuit of interoperability. We will further compare the Cosmos blockchain and other Interchain blockchains. By combining its features, scalability, and security measures with those of other prominent platforms, we aim to comprehensively understand the Cosmos blockchain's position in the broader blockchain landscape [9]. To enhance supply chain transparency and facilitate cross-border financial transactions, we will examine how the Cosmos blockchain's interoperability contributes to solving real-world problems [10]. Figure 2 illustrates various blockchain technologies' TPS capability. Bitcoin and Ethereum have the lowest TPS at 7 and 15, respectively, while Cosmos and Hyperledger show much higher capacities at 10000 and 20000 TPS, respectively. This visualization is crucial for assessing the scalability and efficiency of these blockchains in handling transactions. This paper explores the connections made by the Cosmos blockchain. By dissecting its features, addressing the imperative need for interoperability, reviewing its architecture, comparing it with peers, and presenting real-world applications. Figure 3 shows a simple illustration of cross-chain communication. It can be imagined as an island with different communication channels for each component to transfer information from one part to another. From a user's perspective, we can see that there are several ways that data can flow from one chain to another.

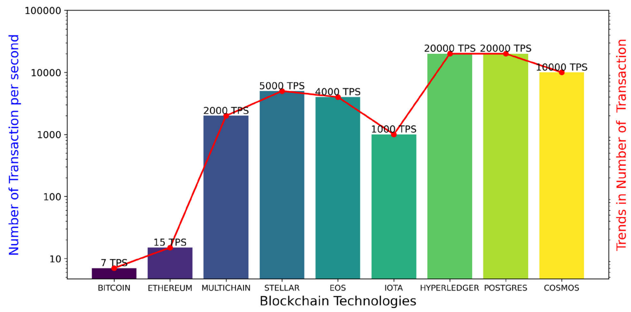

FIGURE 2. Comparison of transaction per second (TPS) across different blockchain technologies.

A. ORGANIZATION OF PAPER

The paper is organized into sections that help explore the features and application of the Cosmos blockchain effectively. The first section, Section I holds the introduction to this study. We illustrate the problem scope of interoperable blockchains and define a domain where their application is needed. In Section II, we explain our motivation for exploring the Cosmos blockchain. In Section III, we explore other solutions made to make blockchains interoperable. Various solutions implemented in this direction have different perspectives and views on the same problem and, hence, different, innovative solutions. A review of these prior works is presented in this section. The application layer of the Cosmos blockchain is explained in subsection IV-A, where we see how Tendermint is working behind the scenes to power the entire Atom blockchain. The third and final subsection "Governance Mechanism" helps us understand the consensus used in the Cosmos blockchain. Section IV we zoom in to see each component separately, such as the Tendermint Core, and then place all the pieces together to build a clear big-picture understanding of the working of Cosmos blockchain in technical aspects. Section V provides a broader look into the structure and architecture of the Cosmos blockchain and how it applies to the interoperable world of blockchains. Its subsection V-A, showcases the key characteristics and highlights of this system and their attributes. Section VI is an individual-level comparison of the Cosmos blockchain with other production-grade solutions. We see how it performs compared to sidechains, Smart Contracts, and Routers. Later, we compare and analyze the data to see where Cosmos blockchain stands in industry-wide use cases. At the end of this section, we provide a Strengths, Weaknesses, Opportunities, and Threats (SWOT). Section VI-E analysis of the Cosmos blockchain. Section VII focuses on the Use Cases and Applications of the Cosmos blockchain. We see where the Cosmos blockchain is already being applied and shows great potential. We see how it can propose the idea of a Central Banking for Digital Currency and its possibilities in gaming. Section VIII discusses what lies ahead for interoperable blockchains and Cosmos blockchain, considering its strengths. The Section IX holds the conclusion of this study. We see what we can use the Cosmos blockchain for and what the prospects are for the Cosmos blockchain to be used in the industry. We also explore the advantages and disadvantages of the Cosmos blockchain and the possibilities it can offer businesses. The detailed structure of this paper is presented in Figure 4, which shows the distribution of the paper and key areas covered in each section.

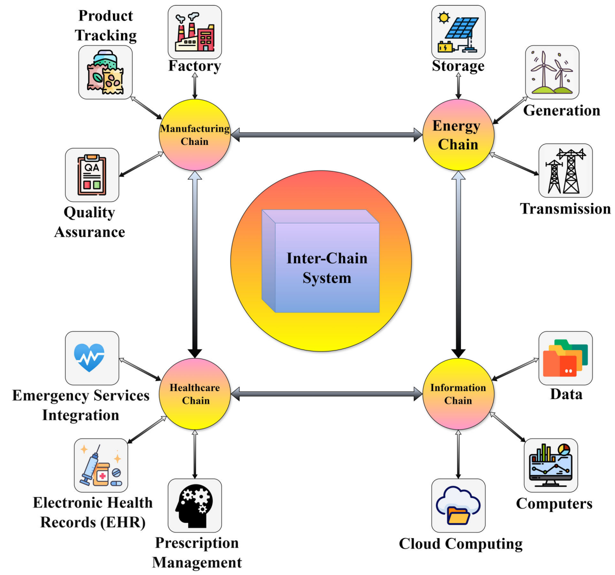

FIGURE 3. Cross-chain communication island.

B. NOVELTY AND CONTRIBUTION

The novelty of this paper lies in its in-depth analysis of the Cosmos blockchain as a revolutionary platform for blockchain interoperability. Cosmos introduces a unique solution for one of the most pressing challenges in blockchain technology: the difficulty of cross-chain communication and scalability. This review highlights Cosmos's Tendermint BFT consensus mechanism and IBC protocol, facilitating secure, scalable, and fast interactions between heterogeneous blockchain platforms [11]. The innovative hub-and-zone architecture sets Cosmos apart, enabling various blockchains to operate autonomously while maintaining the ability to exchange data and assets efficiently. This research positions Cosmos as a significant player in creating an interconnected blockchain ecosystem, thereby addressing the limitations of isolated chains and promoting the broader adoption of Decentralized Applications (DApps) and digital commerce.

The contributions of this paper focus on the technical and practical aspects of Cosmos blockchain and its potential to revolutionize blockchain interoperability. First, it comprehensively reviews the Cosmos architecture, analyzing key features such as Tendermint BFT, the IBC protocol, and the Atom token for governance. Further, it explores how Cosmos ensures secure and efficient communication between diverse blockchains without sacrificing decentralization. The paper compares Cosmos against other blockchain interoperability solutions, such as Polkadot and ICON, showcasing its

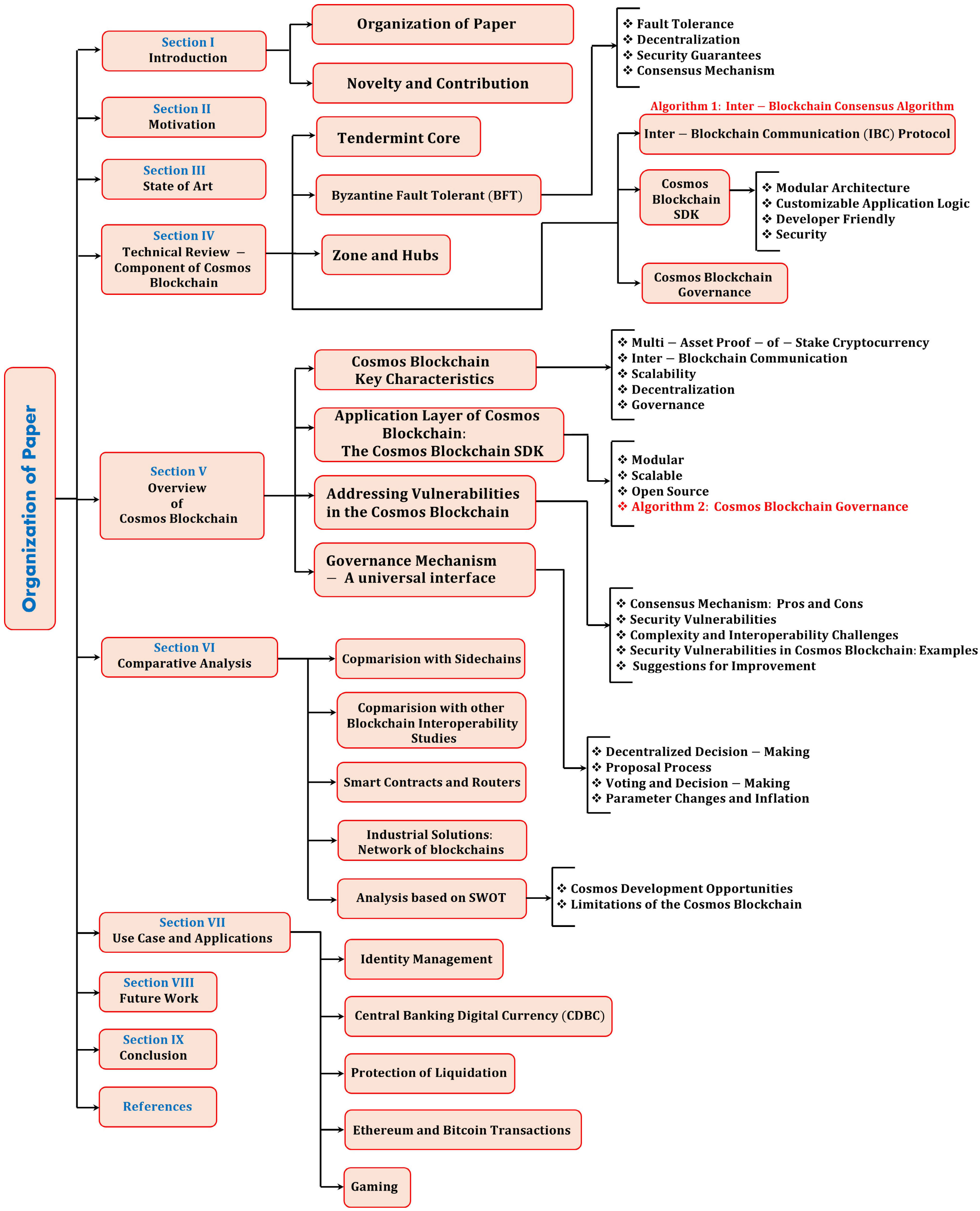

FIGURE 4. Section-wise paper organization showing topics covered.

scalability, security, and governance strengths. The contributions of the paper are shown in Figure 5 and discussed as follows:

i. *Comprehensive Architectural Review:* The paper reviews the analysis of the Cosmos blockchain's architecture, emphasizing its novel hub-and-zone model for achieving cross-chain communication while maintaining decentralization and scalability.

ii. *Inter-Blockchain Communication (IBC) Protocol:* The research explores the IBC protocol's capabilities, which allow the transfer of data and tokens between independent blockchains, promoting interoperability.

iii. *Tendermint BFT Consensus Mechanism:* The paper discusses how the Tendermint BFT consensus mechanism enhances scalability, security, and transaction finality, providing resilience against potential malicious attacks.
iv. *Governance Model:* The paper explores Cosmos's decentralized governance model, which allows for flexible upgrades and parameter adjustments while maintaining the network's security.
v. *Comparison with Other Blockchain Solutions:* The review compares Cosmos with other blockchain solutions like Polkadot and ICON, highlighting Cosmos's superior performance in transaction speed, scalability, and decentralized governance.
vi. *Real-World Applications:* The paper discusses various real-world use cases of Cosmos, including Decentralized Finance (DeFi), supply chain management, and gaming, demonstrating its practical relevance across industries.
vii. *Security Enhancements:* The review identifies potential security vulnerabilities within the Cosmos ecosystem and suggests improvements to enhance its overall robustness.
viii. *Future Implications:* The paper concludes by discussing the future potential of Cosmos in fostering a fully interconnected blockchain ecosystem, which is crucial for advancing decentralized technologies globally.

II. MOTIVATION

The motivation for this paper is rooted in the transformative potential of blockchain technology and its capacity to revolutionize how we conceive of and interact with digital trust systems. The need for a cohesive and interoperable ecosystem becomes increasingly apparent as the blockchain landscape matures. This research focuses on the Cosmos blockchain, a platform that epitomizes the quest for seamless inter-chain communication for the next generation of blockchain applications. The impetus for this study is the recognition that, while blockchain technology has made significant strides, the siloed nature of existing chains hinders the realization of a fully integrated digital economy. Cosmos blockchain offers a solution to this fragmentation with its innovative approach to scalability and interoperability [12]. By exploring the Cosmos blockchain's architectural nuances and operational mechanics, this paper seeks to illuminate the path toward a more interconnected blockchain environment. IBC protocol and BFT consensus mechanism, the Cosmos blockchain network presents a compelling case study for overcoming these challenges. This paper aims to provide a granular analysis of the technical and strategic implications of the Cosmos blockchain's design choices. We will examine how these decisions enable the platform to facilitate communication between diverse blockchains and preserve the core principles of decentralization and security fundamental to blockchain technology [13].

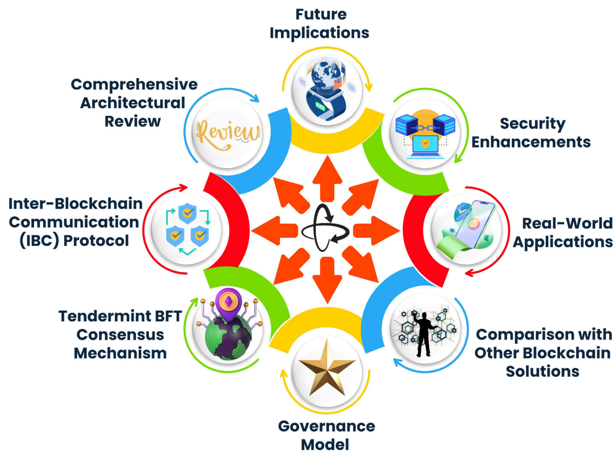

FIGURE 5. Overview of the paper contributions, including architectural review, Tendermint consensus, IBC protocol, governance model, security enhancements, real-world applications, blockchain comparisons, and future implications.

III. STATE OF ART

Blockchain technology, in its entirety, has proven to be a great solution to improve our information systems. Although it offers many features, it lacks several important ones, such as interoperability. Since blockchains are rather closed structures with complete transparency, interoperability is difficult to achieve. This section briefly reviews and discusses work done in this direction. Table 2 relate the concise comparison of different blockchain interoperability solutions, detailing their approaches, features, scalability, security, and applicable use cases [14]. It showcases various strategies, from smart transaction-based communication to specialized architectures like Agri-SCM-BIoT, offering insights into the evolving landscape of blockchain interoperability and its diverse applications across industries [15]. Pillai et al. [16], communication between multiple blockchains is achieved with the help of transactions. These transactions led to a mechanism that could smartly explore transactions and send data from one type of blockchain to another. For example, the chain that contains only information regarding the inventory of a warehouse will now be able to communicate with the chain responsible for its purchase. The mechanism provided solely relied on data transfer that was taking place among the blockchains. The changes made to the database, or simply transactions, led to how these changes can be used to communicate among various blockchains. The solution provided by Ding et al. [17] is a new interoperability framework called Inter-Chain. Inter-chain supports scalable and secure interactions between any pair of blockchains, reliably enabling cross-chain transactions. The framework includes a three-handshaking method for achieving asset transfers between separated blockchains. Its architecture involves subchains, gateway nodes, and validating nodes. This facilitates the seamless exchange of assets and data between different networks. InterChain addresses scalability issues faced by existing solutions for

TABLE 2. Comparison of blockchain types and interoperability solutions.

Blockchain Type	Author(s)	Description	Framework/Architecture	Key Features	Scalability	Challenges Addressed
Smart Transaction-based	Pillai *et al.* [16]	Smart transaction-based communication between blockchains	Transaction-based mechanism	Data transfer, exploring transactions	Addressed through smart transactions	Interoperability, scalability
Inter-Chain	Ding *et al.* [17]	Inter-Chain framework	Three-handshaking method	Subchains, gateway nodes, validating nodes	Scalable and secure interactions	Scalability, privacy, security
Blockchain Router	*Wang et al.* [5]	Blockchain router architecture	Router-based network	Routing mechanism, connectors, PBFT consensus	Private blockchain per user, multi-user scalability	Scalability, user experience
Inter-Blockchain Model	Pascal *et al.* [18]	Inter-blockchain model	Two-in-one chain	Token exchange, ledger interaction	Addressed through ledger interaction	Interoperability, token exchange
Agri-SCM-BIoT	Bhat *et al.* [19]	Agri-SCM-BIoT architecture	Supply chain management with IoT and blockchain	IoT infrastructure with blockchain backbone	Storage, security, interoperability, privacy	Security, privacy, interoperability

blockchain interoperability and emphasizes the importance of privacy and security in cross-chain transactions [20]. The proposed framework aims to provide a comprehensive and efficient solution for enabling interoperability between diverse blockchain ecosystems. Another work motivated by the idea of MultiChain was presented by Wang [5]. The authors introduced a router for blockchains that allows blockchains to communicate with each other in the form of a network similar to the Internet. The internet itself inspires the design concept. Like internet routers in a network, blockchain routers dynamically maintain information registered on sub-chains and link them to the chain network. This allows sub-chains to communicate with each other via a cross-chain communication protocol. Major components of this architecture are a routing mechanism, connectors, a consensus algorithm, and cross-chain communication. Connectors are vital in linking different chains bi-directionally, sending information between sub-chains and the blockchain router. Connectors from a consensus system within each sub-chain collect information on sub-chain blocks for validators. The consensus algorithm this architecture uses is the Practical Byzantine Fault Tolerance (PBFT) Castro and Liskov [21], which involves reliable nodes that package new blocks and participate in voting [22]. These components ensure that the blockchain router acts as a bridge between different chains, ultimately maximizing the potential for interoperability. Performance isolation and scalability again lie as one of the biggest challenges to overcome. The architecture presented in this work enhances the user experience by allotting a private blockchain to each of its users (tenants). This ensured excellent scalability at both the individual level and the multi-user level. With these versatile solutions, inter-blockchain communication seems a lot more approachable. Still, most of the solutions presented have kept scalability at their core. In various use cases, a large-scale user base may not be intended; thus, a targeted service through inter-blockchain communication is required. Blockchain interoperability also aims to reduce the massive sizes of blockchains that have to store different types of information that are sometimes irrelevant to their original purpose. In this direction, Lafourcade and Lombard-Platet [18] sheds more light on an inter-blockchain model's structure. This work addresses the theoretical and practical challenges of making two blockchains interoperable. It further explains that the practical implications of blockchain interoperability are limited to exchanging tokens that already exist on both blockchains rather than enabling direct token transfers between the two networks. Blockchain can be interoperable when creating a two-in-one chain with both ledgers. This way, inter-chain communication can be established, which, in reality, is simply those two ledgers interacting with each other and residing in the same domain of the chain. Also, the entire system will have to maintain the balance of tokens in both ledgers and see if there is any imbalance or a missing token. Agriculture is an area where blockchain is now gaining popularity. In the various stages of growing, maintaining, tracking, selling, and securing crops, blockchain has seen several use cases yet to be explored elsewhere. Thus, Bhat et al. [19] has developed a new system that streamlines the whole process of food crop production. Since consumers demand safe, equitable, and sustainable production, many new technologies, such as blockchain, have been utilized. Therefore, processes that maintain food processing, tracking, and supply chain mechanisms are bound to use their separate blockchains. The proposed Agriculture Supply Chain Management using blockchain and the Internet of Things, referred to as (Agri-SCM-BIoT) is an architecture that can help unify the idea of two or more blockchains having different roles. It aims to address the storage, security, interoperability, and privacy concerns with the help of an IoT infrastructure with blockchain as its backbone. Table 3 shows the comparative analysis of Cosmos' performance and attributes, as evaluated by various authors in the Section III. It highlights key factors such as throughput, interoperability, scalability, governance, security, latency, and other parameters, indicating which aspects each author addresses. Figure 6 shows a hierarchical dendrogram that visualizes the methodology and disadvantages, with color coding based on interoperability. It effectively organizes performance and author metrics, providing a better

TABLE 3. Comparative analysis of cosmos' performance and attributes covered by various authors from state of art section.

Author Reference	TPS	Interoperability	Scalability	Governance	Security	Latency	CM	VC	TF	PF	NS
G. Wang [5]	✓	✗	✓	✗	✓	✓	✓	✗	✓	✗	✓
R. Belchior [9]	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✓
B. Pillai [16]	✓	✓	✓	✗	✗	✓	✓	✓	✗	✗	✓
D. Ding [17]	✗	✗	✓	✓	✓	✗	✓	✗	✓	✗	✓
M. Castro [21]	✗	✓	✓	✗	✓	✗	✓	✗	✓	✓	✓
P. Lafourcade [18]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SA. Bhat [19]	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✓
R. Han [23]	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓
H. Wang [24]	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	✓
B. Sriman [25]	✗	✓	✓	✗	✗	✓	✓	✓	✗	✗	✓
Proposed Paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

* Abbreviations: TPS = Transaction per second, CM = Consensus Mechanism, VC = Validator Count, TF = Transaction Finality, PF = Privacy Features, NS = Network Stability.

understanding of the data relationships. The dendrogram highlights key connections and categories, making it easier to analyze the used references in Section III for better performance analysis. This structure enables more informed decision-making by visually representing the relationships between various factors. The following section will discuss the architecture and components that give the Cosmos blockchain its shape.

IV. TECHNICAL REVIEW - COMPONENTS OF COSMOS BLOCKCHAIN

For a system to be resilient enough to sustain the varied requirements of its users, it requires a strong foundation base with a brilliantly designed architecture that caters to concurrency. The Cosmos blockchain network can effectively harness the power of its underlying components to deliver scalability and cross-chain communication [26]. These components were previously built individually to solve singular problems, but the Cosmos blockchain provides a generic solution for several problems. We will explore the different components in this section and illustrate where each of these components lies in action and how these come together to power a unified solution.

A. TENDERMINT CORE

It is the core component of the Cosmos blockchain Network and is used to power the various zones within the network. It is a consensus engine that provides a high-performance, consistent, and secure PBFT-like consensus algorithm. Figure 7 shows the structural representation of Tendermint Core. It performs well, particularly based on the BFT. The Application Blockchain Interface (ABCI) acts as a bridge between Tendermint Core and the application layer [27]. It defines a clear, standardized interface separating the blockchain consensus engine from the application logic. This separation allows developers to implement their applications or smart contracts independently of the consensus algorithm. It is an asynchronous protocol with fault tolerance. The participants in this protocol are called validators. These validators take part in voting. Validators wait a relatively short time until they receive a complete block from an applicant before voting for it to go to the next round. This time limit makes Tendermint a less synchronous protocol. Only in this situation is the rest of the protocol asynchronous. Figure 8 will help to understand how all these components work together inside the Cosmos blockchain network. The validators only move forward when a block gets 2/3 of the votes [28]. The miner nodes are responsible for solving the crypto puzzle so that the block to be added to the chain can be owned. The sync nodes perform all the synchronous functions. With the help of BFT, Tendermint Core can tolerate up to $1/3^r d$ of a network's machines failing arbitrarily. It is language agnostic and can be programmed using any programming language. It is unlike other consensus algorithms that come pre-packaged with built-in state machines. Through Tendermint BFT, state machines can be replicated onto general computers around the world [29]. It provides prompt confirmations that help finalize a transaction once included in a block. Secure and consistent replication is a fundamental problem in distributed systems, and Tendermint provides all the necessary services to perform replication.

B. BYZANTINE FAULT TOLERANT (BFT)

BFT is a class of consensus algorithms designed to achieve agreement among a distributed network of nodes, even in the presence of faulty or malicious nodes. "Byzantine" refers to the Byzantine Generals' Problem. This classic computer science problem illustrates the challenges of achieving consensus in a distributed system when some nodes may behave arbitrarily or maliciously [30], [31]. The Byzantine Generals' Problem describes the problem where a common enemy is at focus, and all the attackers (King's generals) must agree to a single strategy to ensure a win. The problem arises when one or more attackers behave unusually or become corrupt. This problem becomes particularly challenging when communication is asynchronous, meaning there is no

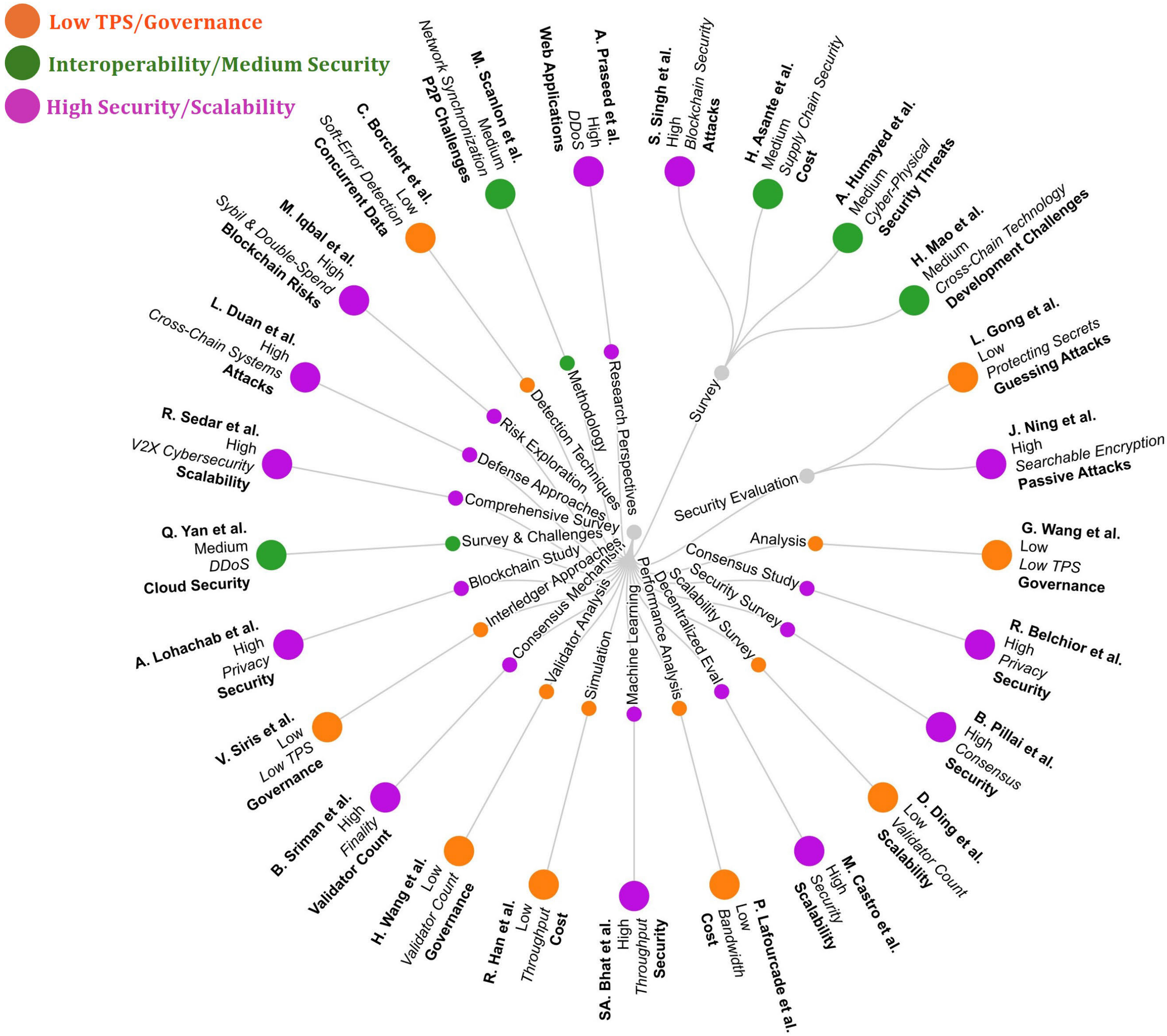

FIGURE 6. Dendrogram visualizes hierarchical relationships using methodology used and disadvantages, with color representing interoperability and labels showing author names and performance metrics.

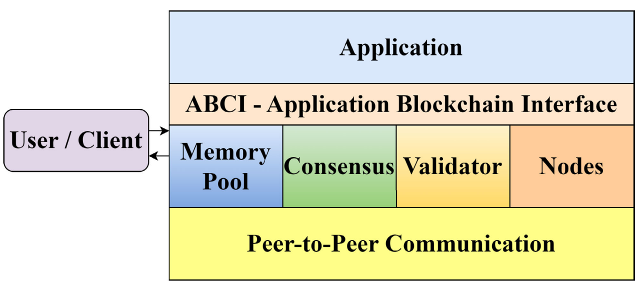

FIGURE 7. Structure of the tendermint core.

guarantee about the time it takes for messages to be delivered, and therefore, the uncertainty about the number and behavior of faulty components [21].

i. *Fault Tolerance:* BFT algorithms are designed to tolerate a certain number of faulty or malicious nodes within the network without compromising the overall consensus process. This fault tolerance ensures that the network can continue to operate and reach agreement even in the presence of adversarial behavior [32].
ii. *Decentralization:* BFT algorithms typically operate decentralized, with no single point of control or authority. This decentralization helps prevent a single point of failure and enhances the security and resilience of the network.
iii. *Security Guarantees:* BFT algorithms provide strong security guarantees, ensuring the network can operate correctly and reach consensus, even in adversarial behavior or network disruptions.

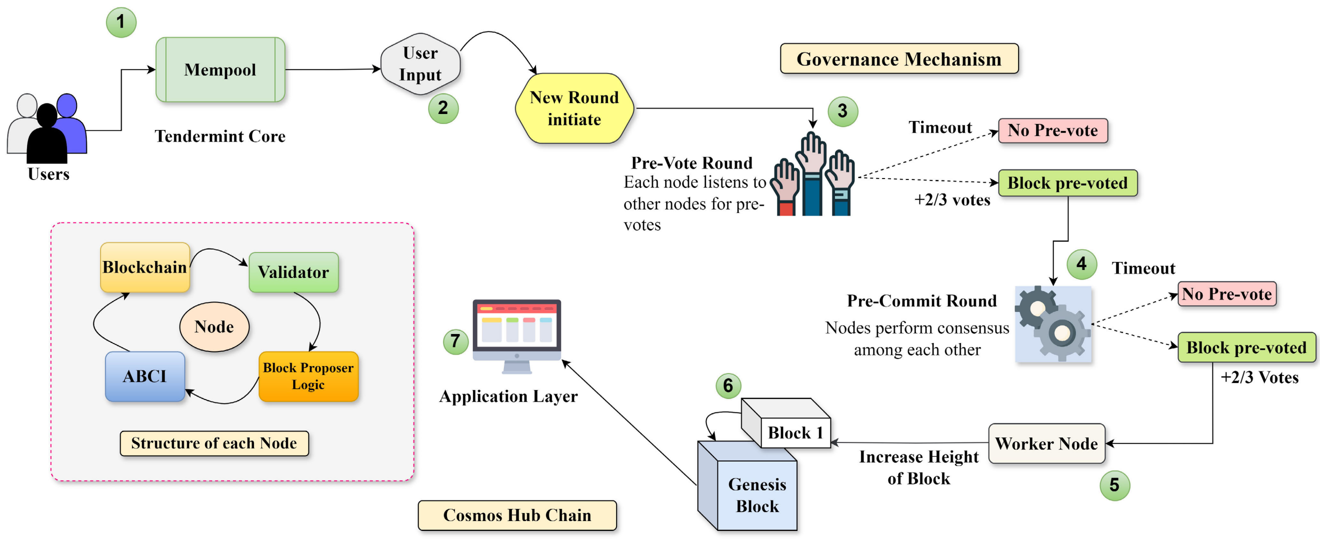

FIGURE 8. Visualizing the interaction between cosmos blockchain components, this flow illustrates nodes collaborating as a network of interconnected chains.

iv. *Consensus Mechanism:* BFT algorithms use a consensus mechanism to achieve agreement among the nodes in the network. This mechanism involves a series of rounds of communication and voting, during which nodes exchange messages and agree on the state of the network.

C. ZONE AND HUBS

Zone and Hubs are independent blockchains powered by Tendermint BFT and can be plugged into the Cosmos blockchain Hub. Each zone can have its own constitution and governance mechanism, allowing users to experiment with different policies and governance models. A zone is an independent blockchain powered by Tendermint BFT plugged into the Cosmos blockchain hub. Each zone can have its own constitution and governance mechanism, allowing users to experiment with different policies and governance models. Zones can be used to create specialized blockchains for specific use cases, such as gaming, supply chain management, or identity verification [33]. A hub, such as the Cosmos blockchain hub, is a blockchain that can host a multi-asset distributed ledger. This way, the tokens that exist can be transported between chains. In Figure 8, the Cosmos blockchain Hub chain includes each new block upon validation completion.

D. INTER-BLOCKCHAIN COMMUNICATION (IBC) PROTOCOL

The IBC protocol is a communication protocol that enables different zones within the Cosmos blockchain Network to communicate with each other and transfer tokens securely and quickly without the need for exchange liquidity between them. Blockchains' primary communication issues are Interoperability, Scalability, and a Consensus Mechanism [34]. The IBC protocol handles these issues of islands of redundant and inconsistent information in blockchain systems by enabling different blockchain systems to communicate and transact without intermediaries. IBC uses efficient routing algorithms to dynamically update routing paths between nodes in different blockchain systems, allowing for the seamless transfer of data and transactions [35], [36]. When a transaction involving two different blockchain systems is generated, IBC analyzes and packs the transaction into a specific form to adapt to the destination blockchain system. This approach ensures that all relevant parties validate and agree upon transactions and that data is stored consistently and securely across different blockchain systems [37]. The Algorithm 1 will help understand the working of the IBC protocol. The algorithm illustrated gives more clarity on

Algorithm 1 Inter-Blockchain Consensus Algorithm

Input: Transaction, tx
Output: Processed block
Step 1: Get leader: $leader = proposer(h, r)$
begin
  if *self is leader* **then**
    $block = processedBlock(tx)$
    Broadcast block: $broadcast(block)$

Step 2: Receive and Process Block
begin
  if *block is received* **then**
    Vote for the block: $vote = verify(block)$
    Broadcast the vote: $broadcast(block)$

Step 3: Handle Votes
begin
  if $1/3$ *reject vote received* **then**
    Change round: $round = round + 1$
  if $2/3$ *approve vote received* **then**
    Change height: $height = height + 1$

Step 4: Store Transaction and Block
begin
  Store tx and $block$: $store(tx, block)$

how IBC powers the core functionality of the Cosmos blockchain. In the first step, we select a ***leader*** known as the proposer for a specific height and round. *Height* indicates the progression of the state of the blockchain. And ***round*** allows for another attempt at achieving consensus [38]. The proposer is responsible for initiating the consensus process for the given transaction. Followed by the next *Block* is processed. If the current node is the leader, it processes the transaction to create a block. This block contains the relevant transaction data and is prepared for broadcasting to the network. After this, the leader broadcasts the created block to the network, allowing other nodes to receive and validate the block. Upon receiving the block, *Vote Verification* takes place, verifying the validity and casting a vote to approve or reject the block. This voting process ensures that consensus is reached regarding the transaction's validity. The algorithm then counts if sufficient nodes either approve or reject the block. The algorithm stores the validated transactions and the corresponding block, ensuring that the agreed-upon transactions are securely recorded in the blockchain.

E. COSMOS BLOCKCHAIN SDK

The Cosmos blockchain SDK is a framework for building custom blockchain applications that can be integrated with the Cosmos blockchain Network. It provides a modular architecture that allows developers to customize their blockchain applications to meet their specific needs [39], [40]. The key aspects of Cosmos blockchain SDK are the following:

i. *Modular Architecture:* The Cosmos blockchain SDK is modular, allowing developers to customize and assemble various modules to create blockchain applications tailored to their specific use cases. This modular approach provides flexibility and extensibility, enabling developers to build applications with the desired functionality.
ii. *Customize Application Logic:* Developers can define custom application logic using the Cosmos blockchain SDK, including creating custom tokens, governance mechanisms, staking, and more. This allows for creating blockchain applications that meet specific business requirements and use cases [41].
iii. *Developer Friendly:* The Cosmos blockchain SDK is designed to be developer-friendly, with extensive documentation, tutorials, and resources to support developers in building blockchain applications. It also provides a testing framework for writing and running automated tests to ensure the reliability and correctness of applications.
iv. *Security*: The Cosmos blockchain SDK provides tools and features to ensure the security and scalability of blockchain applications built using the framework. This includes support for Tendermint BFT consensus, which provides a high-performance, consistent, and secure consensus algorithm.

F. COSMOS BLOCKCHAIN GOVERNANCE

Cosmos blockchain Governance makes and implements decisions within the Cosmos blockchain Network. It is a decentralized decision-making process involving a distributed organization of validators responsible for voting on proposals [33]. The governance mechanism is primarily based on the Tendermint Core, where its nodes act rule-based to select or reject the entry of a block into the network, as shown in Figure 8.

V. OVERVIEW OF COSMOS BLOCKCHAIN

Blockchain interoperability is an important feature that many businesses and teams are interested in, as it allows different blockchain networks to communicate and function together smoothly, enabling more efficient processes and broader applications of blockchain technology. Interconnected blockchains can ensure a secure tunnel environment for all the services owned by an organization. They can practically pursue their operations normally and remain highly secure with minimum chances of data mutation and unauthorized access. As discussed in the literature review section, some limitations must be overcome to have an effective network of blockchains, each responsible for its functions. To address this problem, Jae Kwon and Ethan Buchman created the Cosmos blockchain in 2016 [42]. Cosmos blockchain originated from Tendermint, the underlying service that powers interoperability features. It aimed to address Bitcoin's proof-of-work consensus algorithm's speed, scalability, and environmental issues. The goal of Tendermint was to provide a high-performance, consistent, and secure consensus engine for blockchain applications. Tendermint utilizes a BFT consensus algorithm to turn any deterministic black box application into a distributed replicated blockchain. In 2016, the Tendermint team created a new blockchain network called Cosmos blockchain, using the existing capabilities to allow multiple parallel blockchains to interoperate while retaining their security properties [42]. In the Cosmos blockchain, many independent blockchains work in zones. Tendermint BFT, a high-performance, reliable, secure, and practical BFT-like consensus engine, provides the power behind these zones. Further details on this architecture are explained in Section IV. In this direction, the Cosmos blockchain network is designed to be an open-source network of distributed ledgers that can serve as a new foundation for future financial systems based on principles of cryptography, sound economics, consensus theory, transparency, and accountability. The Tendermint BFT consensus algorithm powers the Cosmos blockchain hub, the first public blockchain in the network. One of the key purposes of the Cosmos blockchain hub is to facilitate interoperability and communication between different zones through the IBC protocol. This protocol allows tokens to be transferred securely and quickly between zones without the need for exchange liquidity between them [43]. Cosmos Blockchain Hub tracks the total amount of tokens held by each zone, thereby isolating each zone from the failure of other zones. In the following discussion, we have listed the key features and capabilities.

A. COSMOS BLOCKCHAIN KEY CHARACTERISTICS

In this subsection, we mention some key characteristics of the Cosmos blockchain drawn from its core capabilities, which bring much value to the end user.

i. *Multi-Asset Proof-of-Stake Cryptocurrency*: The Cosmos blockchain Hub is a multi-asset proof-of-stake cryptocurrency that allows users to hold and transfer different types of tokens. The Cosmos blockchain Hub is designed to be a simple governance mechanism that enables the network to adapt and upgrade [44].
ii. *Inter-Blockchain Communication*: The Cosmos blockchain allows for the secure and fast transfer of tokens between different zones through the IBC protocol. This protocol enables different zones to communicate with each other and transfer tokens without the need for exchange liquidity between them.
iii. *Scalability*: The Cosmos blockchain is designed to be highly scalable, allowing for many parallel blockchains to interoperate while retaining their security properties. This is achieved through Tendermint BFT, which provides a high-performance, consistent, and secure consensus engine [23].
iv. *Decentralization*: The Cosmos blockchain is designed to be decentralized, with no single point of failure. The network is secured by a globally decentralized set of validators that can withstand severe attack scenarios [45].
v. *Governance*: The Cosmos blockchain offers high flexibility. It allows different zones to have their governing mechanisms. Thus, customization is offered at an atomic level in the entire network of chains.

B. APPLICATION LAYER OF COSMOS BLOCKCHAIN - THE COSMOS BLOCKCHAIN SDK

This part of the Cosmos blockchain contributes to overcoming challenges faced with usability. With multiple chains to handle and integrate, there is an imminent challenge of interacting with the interface of these chains. Thus, a governing mechanism to which all chains can abide will be required to act as a universal interface. The Cosmos blockchain Software Development Kit (SDK) is a package of modules that enables developers to create and deploy apps seamlessly [46]. This provides the required level of abstraction needed so that they can focus more on application logic. This way, Cosmos Blockchain SDK allows developers to create and launch new blockchains and connect different blockchains. This SDK offers several features.

i. *Modular*: Comsos provides different modules to suit the specific requirements of your project. Thus, creating a blockchain with tailor-made features targeting a specific or generic use case is easier [6]. This allows developers and users to handle the changing use cases, thus making maintaining dependencies easier.
ii. *Scalable*: To match the desired throughput of transactions and data flow, we can run parallel chains inside the Cosmos blockchain SDK. Thus, this can adjust to the ever-growing demands of the user base. This offers to apply Continuous Integration/Continuous Deployment (CI/CD) to some extent, thus becoming a viable solution for the cloud-based delivery of services [47].
iii. *Open Source:* If developers of a specific community or organization feel the need for a capability or a feature that will benefit their use-case or is an existing problem in the existing Cosmos blockchain architecture, they can contribute to adding these changes to the code base [48]. With an open source developer community. It allows the creation of better applications with collaboration. There are discussion forums that allow any bug or an open issue to be drawn to stakeholders' notice so that it can be fixed. This also drives worldwide support through ideas and suggestions from the Cosmos Open Source repository.

Algorithm 2 Cosmos Blockchain Governance

Input: Gaming Tokens from Zone A, T_A; Destination Zone, Z_B
Output: Equivalent DeFi Tokens (Zone B)
Step 1: Zone A initiates transfer
begin
  Read total Tokens of Zone A: $token_A = getToken(Z_A)$;
  Create a model for tokens;
Step 2: Inside Cosmos blockchain Hub
begin
  Get model for tokens from Zone A: $getModel(token_A, Z_A)$;
  if $token_A > T_A$ **then**
    Create model for Zone B;
    Get model for tokens from Zone B: $M_B = getModel(token_A, Z_B)$;
    Broadcast to Zone B: $broadcastIBC(Zone_B)$;
  Zone B mints DeFi tokens: $T_D = minter(M_B)$;
  Transfer DeFi tokens to the user.

In Algorithm 2, we detail the inter-zone token transfer algorithm as follows:

Zone A Initiates Transfer to Alice, a user in Zone A, who wants to transfer her gaming tokens to Zone B (DeFi blockchain [25]). Alice initiates the transfer by specifying the number of gaming tokens she wants to move. The Cosmos blockchain hub acts as the central router, connecting different zones within the blockchain network. The transaction is verified when Alice's request reaches the Cosmos blockchain Hub. It ensures that Zone A has enough tokens to back the transfer. The Hub then creates a representation of Alice's gaming tokens in Zone B. Using the IBC protocol, also mentioned in Algorithm 1, the Cosmos blockchain Hub communicates with Zone B. Zone B creates actual DeFi tokens that are equivalent to the Hub's representation. Alice now holds her DeFi tokens in Zone B, bridging the gap between gaming and DeFi ecosystems.

C. ADDRESSING VULNERABILITIES IN THE COSMOS BLOCKCHAIN

Cosmos blockchain offers significant advancements in scalability and interoperability through its Tendermint consensus

FIGURE 9. Highlighting the various security vulnerabilities in the cosmos blockchain using word cloud diagram.

mechanism and IBC Protocol [49], [50]. It is essential to acknowledge and address its vulnerabilities. This section objectively analyzes the pros and cons of its consensus mechanism, security vulnerabilities, and overall complexity. It proposes suggestions to solve these issues and enhance the robustness of the Cosmos blockchain. Figure 9 shows a word cloud diagram highlighting the key issues and vulnerabilities in the Cosmos blockchain. The diagram visually represents technical and operational challenges such as network scalability, security concerns, interoperability issues, and governance complexities. This visual representation helps to identify and prioritize areas that require attention and improvement to ensure the robustness of the blockchain network.

1) CONSENSUS MECHANISM: PROS AND CONS

Pros:

i. *Byzantine Fault Tolerance:* The Tendermint consensus mechanism provides high fault tolerance, ensuring the network remains operational even if some nodes are compromised.

ii. *Finality:* Transactions achieve finality quickly, reducing the risk of forks and double-spending attacks.

iii. *Energy Efficiency:* Compared to proof-of-work mechanisms, Tendermint is more energy-efficient, which makes it more environmentally friendly.

Cons:

i *Validator Centralization:* The consensus mechanism can lead to centralization if a few validators control a significant portion of the voting power.

ii *Sybil Attacks:* Without adequate security, the network may be vulnerable to Sybil attacks, where an attacker could create numerous identities to gain disproportionate influence.

2) SECURITY VULNERABILITIES

Potential Attack Vectors: Despite its robust design, the Cosmos blockchain is not immune to security threats. Potential attack vectors include:

i. *Double-Spending:* Although Tendermint provides finality, double-spending attacks could still occur if validators are compromised.

ii. *DDoS Attacks:* The network could be susceptible to Distributed Denial-of-Service (DDoS) attacks to disrupt validator operations.

iii. *Smart Contract Exploits:* As with any blockchain, vulnerabilities in smart contracts could be exploited, leading to significant financial losses.

3) COMPLEXITY AND INTEROPERABILITY CHALLENGES

i. *Complex Architecture:* The interconnected nature of the Cosmos ecosystem, while beneficial, introduces complexity that can pose challenges in maintenance and scalability.

ii. *Inter-Blockchain Communication:* While the IBC Protocol facilitates seamless transactions across different blockchains, ensuring secure and efficient communication remains challenging, particularly as the network grows.

4) SECURITY VULNERABILITIES IN COSMOS BLOCKCHAIN: EXAMPLES

The Cosmos blockchain has encountered several notable security vulnerabilities that highlight the unique challenges within its ecosystem [26]. One significant example is the Redelegation Attack, where malicious actors exploit the delegation mechanism to quickly change their validator, gaining undue influence over the network and potentially manipulating consensus decisions [51]. Another crucial issue is the Denial of Service (DoS) Attack, wherein attackers flood the network with excessive transactions, overwhelming validators and disrupting legitimate activity [52]. The Reentrancy Vulnerability, specifically the Dragonberry Vulnerability, exploits recursive calls in smart contracts, allowing attackers to withdraw more funds than intended [24]. The Slow Convergence in Mathematical Operations can lead to inefficiencies in transaction validation, while Authentication Bypass Vulnerabilities allow unauthorized access to critical functions [53]. Vulnerabilities in the IBC protocol, such as Proof of Absence Manipulation (PAM), enable attackers to falsely claim the absence of transactions, undermining the trust between chains [54]. Packet Forgery and exploits within IBC channels can allow malicious actors to inject harmful transactions into the network [55]. Figure 10 shows examples of security weaknesses in the Cosmos blockchain. We found these weaknesses in blog posts and discussions from the Cosmos blockchain's Discord community, giving a clearer understanding of the network's security challenges.

i. *Dragonberry Vulnerability (Repeated Action Attack):* The Dragonberry Vulnerability, known as the Repeated

FIGURE 10. Illustrative examples of security vulnerabilities in cosmos, derived from blog posts and discussions on the discord community of cosmos blockchain.

Action Attack, involved a critical flaw in how Cosmos verified the validity of transactions between blockchains [12], [62], [63]. The vulnerability allowed bad actors to send fake proofs, exploiting the system's lack of proper checks [64], [65]. This could have led to attackers successfully tricking the system into accepting false information repeatedly, potentially resulting in fund theft or confusion across different blockchains. The Cosmos team implemented a software patch to add extra verification layers to resolve the issue, ensuring that false proofs are detected [66]. They collaborated with key stakeholders to deploy this fix across multiple blockchains, effectively preventing such attacks before they could occur [51].

ii. *IBC Timeout Attack (Fake Timeout Trick):* The IBC Timeout Attack, often called the Fake Timeout Trick, targeted Cosmos's IBC protocol, facilitating token transfers between different blockchains [11]. The protocol included a built-in timer that refunded tokens if the transfer was not completed within a certain time frame [67]. This mechanism is vulnerable to manipulation. Attackers could send false messages to make it appear that a transfer had failed when, in fact, it had succeeded [68]. By doing so, they could retrieve their tokens while keeping the tokens they had received, effectively doubling their assets. To address this vulnerability, the developers introduced more robust checks to verify the validity of timeout messages, thereby preventing attackers from exploiting the system's refund mechanism [69].

iii. *ICS-23 Proof Forgery (Fake Proof Attack):* Another significant issue is ICS-23 Proof Forgery, also known as the Fake Proof Attack (FPA). This vulnerability is tied to the system Cosmos used to confirm the occurrence or non-occurrence of transactions, a system that relied on proofs [70]. An exploitable flaw in this proof mechanism allowed attackers to create fake proofs. Such fake proofs could falsely claim that a transaction occurred or did not occur, allowing attackers to manipulate the network and steal funds. To solve this risk, the team improved the proof verification system, ensuring that all proofs were authentic and valid, thereby preventing any acceptance of forged proofs within the network [51].

iv. *Staking Vulnerability (Penalty Trick):* The Staking Vulnerability, referred to as the Penalty Trick, exploited Cosmos's validator mechanism, in which validators secure the network by staking tokens [71]. Misbehaving validators could be penalized through a process called slashing [72]. There is a loophole that allows attackers to falsely frame honest validators for misbehavior, causing them to lose their staked tokens. This vulnerability also allowed malicious validators to exploit the system, evading penalties and potentially destabilizing the network [73]. To counteract this, the developers enhanced the checks surrounding validator actions, ensuring that penalties were only applied in cases of genuine misbehavior, making the network fairer and more secure [74].

v. *Authentication Bypass (Skipping Login Attack):* The Authentication Bypass, or Skipping Login Attack, exposed a flaw in the role-based permission system of Cosmos, where some critical tasks required specific permissions. Attackers discovered a way to bypass the

TABLE 4. Comparison of blockchain types, consensus mechanisms, and average transaction time.

Blockchain	Type	Consensus	Finality	Blocktime (s)	Confirmation After	Average Transaction Time
Bitcoin [56]	Public	PoW	No	600	6 blocks	10–60 minutes
Ethereum [57]	Public	PoW	No	15	7 blocks	13 seconds upwards to 5 minutes
Stellar [58]	Public	SCP	Yes	5	1 block	5 seconds
EOS [59]	Public	dPoS	Yes	0.5	1 block	average of 0.25 seconds
IOTA [60]	Public	IOTA	Yes	60	1 block	1.9 seconds
Hyperledger [59]	Private	PoET	Yes	20	1 block	0.5 seconds
Multichain [59]	Private	PoA	Yes	15	1 block	3–30 minutes
Cosmos [61]	Public	BFT	Yes	6	1 block	55.448 seconds

login process, gaining unauthorized access to sensitive roles within the network [75]. This allowed them to make unauthorized changes, disrupt the network, or steal funds. To address this issue, the Cosmos team reinforced the security checks. It introduced additional security, including Multi-Factor Authentication (MFA), making it more challenging for attackers to bypass the authentication process [76].

vi. *Double-Spend Attack (Using the Same Tokens Twice):* The Double-Spend Attack (DSA) involved tricking the blockchain system into using the same tokens more than once, undermining the basic principle of blockchain—that each token can only be spent once [77], [78]. An attacker could potentially control multiple validators, thereby splitting the network and using the same tokens on different versions of the blockchain [79]. This effectively allowed them to spend the same tokens twice. To prevent this attack, Cosmos implemented stringent requirements for validator consensus, ensuring that a majority of validators must agree on every transaction. The network imposed strict rules and penalties for misbehavior, thus reducing the chances of a successful double-spend attempt [80].

5) SUGGESTIONS FOR IMPROVEMENT

i. *Decentralization Measures:* To reduce validator centralization, the Cosmos network could implement measures such as random validator selection or increased validator incentives for smaller participants.

ii. *Enhanced Security Protocols:* Implementing advanced security protocols, such as multi-signature wallets and hardware security modules, can help protect against attacks [36], [81].

iii. *Regular Audits and Upgrades:* Conducting regular security audits and system upgrades can identify and rectify vulnerabilities promptly.

iv. *Simplifying Architecture:* Streamlining the blockchain architecture and improving documentation can reduce complexity and make it easier for developers to build on the Cosmos platform.

D. GOVERNANCE MECHANISM - A UNIVERSAL INTERFACE

An interesting aspect of this network is the governance mechanism that has been implemented, keeping in mind the actual nature of a blockchain. This governance mechanism enables the network to adapt, upgrade, and coordinate changes to the blockchain, such as variable parameters of the system, software upgrades, and constitutional amendments. The key aspects that this mechanism delivers are:

i. *Decentralized Decision-Making:* The governance mechanism involves a distributed organization of validators responsible for voting on proposals. This decentralized decision-making process ensures that no single entity has unilateral control over the network [86], [87].

ii. *Proposal Process:* Any changes to the Cosmos blockchain Hub, such as parameter adjustments, software upgrades, or constitutional amendments, are proposed and voted upon by validators. Proposals require a deposit of tokens, and voters can choose to take the deposit if the proposal is deemed spam.

iii. *Voting and Decision-Making:* Validators and delegators can vote on proposals using options such as Yea, YeaWithForce, Nay, NayWithForce, or Abstain [88]. A strict majority of Yea or YeaWithForce votes (or Nay or NayWithForce votes) is required for a proposal to be decided as passed or failed. A veto mechanism allows a minority to veto a majority decision, but this action has penalties.

iv. *Parameter Changes and Inflation:* Parameters of the Cosmos blockchain Hub, such as block times, transaction fees, and inflation rates, can be changed by passing ParameterChangeProposals. This includes inflation and reserve pool funds that can be spent by passing BountyProposals [38].

VI. COMPARATIVE ANALYSIS

In this section, a review of all the available inter-blockchain communication solutions is discussed. We have classified the available solutions into four categories: sidechain solutions, blockchain routers, smart contracts, and industrial solutions.

TABLE 5. Comparative analysis of features in current Sidechain network.

Sidechain	Base Chain	Type	Architecture	Consensus
RSK [82]	Bitcoin	2-Way Peg	Miners, Nodes, Federation	Proof-of-Work
Plasma [83]	Ethereum	Tee hierarchy	Miners, Nodes	Proof-of-Stake
POA Network [84]	Ethereum	Proxy to Ethereum	Validators, Nodes	Proof-of-Authority
Mimblewimble [85]	Bitcoin	Connects Grin to Bitcoin	Miners	Mimblewimble

Table 4 shows a comparative overview of blockchain systems and highlights key metrics such as type, consensus mechanism, block time, and transaction time for blockchains like Bitcoin, Ethereum, and Cosmos, illustrating their varied performance and application potential. It includes public and private blockchains such as Bitcoin, Ethereum, and Hyperledger. A noteworthy inclusion is Cosmos, a public blockchain that employs the BFT consensus mechanism [74]. Unlike Bitcoin and Ethereum, which do not guarantee finality and require longer block times (600s and 15s, respectively), Cosmos achieves transaction finality, has a block time of just 6 seconds, and requires only one block for confirmation, resulting in a specific average transaction time of approximately 55.448 seconds. This makes Cosmos an interesting case of efficiency and speed in transaction processing compared to other blockchains, showcasing its potential for high-speed applications [89]. We have conducted empirical research and consulted several reputable sources to determine the average transaction time, reviewed existing literature and studies for each blockchain, provided insights into transaction times under typical network conditions, and analyzed transaction data from the respective blockchain networks to ensure accuracy and relevance of transaction time. There are various ways in which interoperability can be achieved. Sidechains and Cross-Chains are the broad categories that have shown promising results. We compare the Cosmos blockchain extensively with other available industrial solutions and sidechains to understand how they differ from full-fledged blockchain networks and what led to the need for networks.

A. COMPARISON WITH SIDECHAINS

Sidechains were introduced as chains pegged for asset transfer between Bitcoin chains and other cryptocurrencies. Sidechains are limited to a one-to-one transfer relationship, and the asset count does not increase, which means for a fixed number of assets, we can do a single chain-to-chain transfer of assets using sidechains [90]. The following table explores various side-chain solutions. Table 5 has shown that the various sidechain projects had a variety of implementations even when running on either the Bitcoin or Ethereum blockchain. RSK [91], Plasma [83], and POA Network [84] all have their architecture based on miners and nodes and still follow different consensus mechanisms. POA only drives the complexity of the process to a higher level, and while it allows the inter-chain transfer of assets, it is still a transfer between the same types of blockchains. This is where sidechains fell short on functionalities [92]. Cosmos and Sidechain blockchain interoperability exhibit distinct architectural approaches to connecting multiple blockchains [9], [12], [37], [93]. Cosmos follows a hub-and-zone model, where numerous independent blockchains, called zones, communicate through a central Cosmos Hub using the IBC protocol [54]. This model allows for decentralized and secure exchanges of tokens and data between the zones and emphasizes decentralized governance. In contrast, sidechain blockchain interoperability operates through a main blockchain (such as Ethereum or Bitcoin) connected to various sidechains using smart contracts or a two-way peg mechanism [92]. The sidechain model relies on a more centralized structure, where the main blockchain is crucial in coordinating and managing asset transfers between itself and the sidechains [94]. This architectural difference highlights how Cosmos focuses on decentralization with secure communication, while sidechains maintain a more centralized control through the main blockchain. Figure 11 shows a detailed comparison of the architecture of these two interoperability models, highlighting their structure and differences. Table 6 shows the architectural and protocol-based comparison between Cosmos and sidechain blockchain interoperability. It highlights key differences in architecture, interoperability protocols, centralization, security models, scalability, and trust models, providing a comprehensive overview of their distinct approaches to blockchain interoperability. Figure 12 compares transaction finality time between Cosmos and Sidechain networks as Transactions per Second (TPS) increase. Cosmos consistently achieves lower finality times, making it more efficient, especially at higher TPS, due to its faster consensus mechanism and better scalability. Figure 13 shows the CPU utilization of Cosmos and Sidechain networks across different transaction costs (gas fees). Cosmos consistently exhibits lower CPU utilization, especially at higher transaction costs. For instance, at a gas fee of 0.6, Cosmos utilizes around 45% CPU, while Sidechain reaches 55%, indicating that Cosmos is more resource-efficient. Figure 14 shows the latency comparison between Cosmos and Sidechain networks as block sizes increase. Cosmos consistently demonstrates lower latency, with 150 ms at a 6 MB block size, compared to Sidechain's 250 ms. This lower latency across all block sizes indicates that Cosmos offers faster processing, making it more efficient in handling larger block sizes. Figure 15 compares consensus algorithm efficiency between Cosmos and Sidechain networks as memory usage increases. Cosmos consistently demonstrates

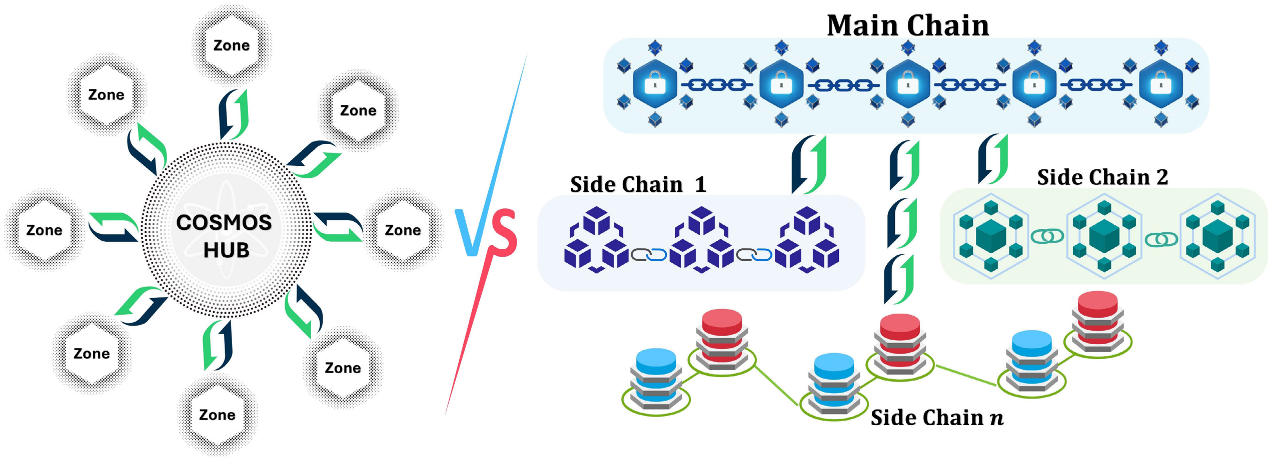

FIGURE 11. Comparison of cosmos hub and sidechain architectures, highlighting their distinct interoperability structures and integration approaches.

TABLE 6. Architectural and protocol-based comparison between Cosmos and Sidechain blockchain interoperability.

Feature	Cosmos Blockchain Interoperability	Sidechain Blockchain Interoperability
Architecture	Cosmos Hub connecting independent zones via IBC	Parent chain connected to multiple sidechains
Interoperability Protocol	IBC	Two-way peg and bridges
Centralization	Decentralized hub model	Centralized control through parent chain
Security Model	Each zone maintains its own security, coordinated by Hub	Security often depends on the parent chain
Scalability	Highly scalable with seamless addition of new zones	Scalable with modular sidechains
Trust Model	Trustless interaction using IBC	Trust assumptions due to bridge validators

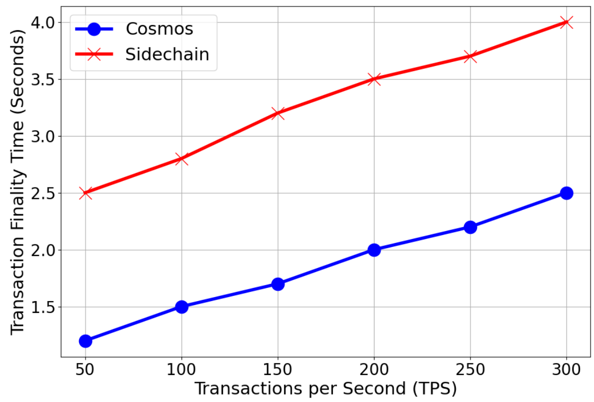

FIGURE 12. Comparison of transaction finality time between cosmos and sidechain networks as transactions Per Second (TPS) increase.

higher efficiency, maintaining around 85% efficiency across all memory levels, while Sidechain efficiency peaks at about 70%. This indicates that Cosmos is more effective at utilizing memory to achieve better consensus, making it more efficient, especially under higher memory usage conditions.

B. COMPARISON WITH OTHER BLOCKCHAIN INTEROPERABILITY STUDIES

Comparing Cosmos with other prominent blockchain interoperability solutions is crucial to understanding its unique advantages and positioning in the field [95]. Notable studies in this area include Polkadot, Interconnected Network (ICON), and Alliance of Interoperable Networks (AION). Polkadot employs the Nominated Proof-of-Stake (NPoS) mechanism and Cross-Chain Message Passing (XCMP) protocol to achieve high scalability and near-instantaneous transaction finality [12]. ICON utilizes the Loop Fault Tolerance (LFT) consensus and Blockchain Transmission Protocol (BTP) to enhance connectivity among multiple blockchains, focusing on Decentralized Finance (DeFi) applications [59]. AION uses the BFT mechanism and AION Interchain Communication (AIC) protocol, targeting enterprise applications with high security and near-instantaneous transaction finality [96]. Each of these solutions contributes uniquely to the field of blockchain interoperability. Still, Cosmos stands out with its Tendermint consensus mechanism and IBC protocol, ensuring high scalability, security, and seamless cross-chain transactions, thus positioning itself as a pivotal player in revolutionizing blockchain ecosystems and their impact on digital commerce and governance [9]. Table 7 below compares these key features across different blockchain interoperability solutions.

C. SMART CONTRACTS AND ROUTERS

A different approach is using blockchain nodes to act as routers between different chains that can direct requests to each other. There were a few proposed solutions; an analysis of these and a side-by-side comparison are presented below. Wang proposes a multiple-chain structure for the robust transfer of assets [5]. The architecture had four layers. The basic layer is, for application purposes, a blockchain

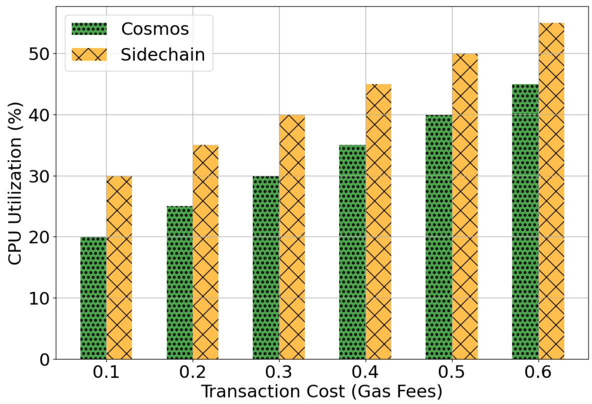

FIGURE 13. Comparison of CPU utilization (%) between cosmos and sidechain networks for different transaction costs (Gas Fees).

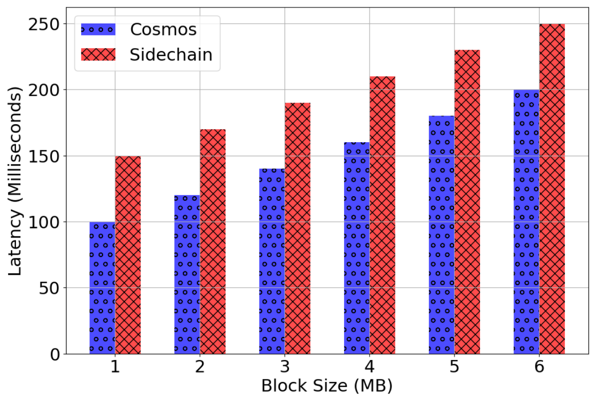

FIGURE 14. Comparison of latency between cosmos and sidechain networks for different block sizes (MB).

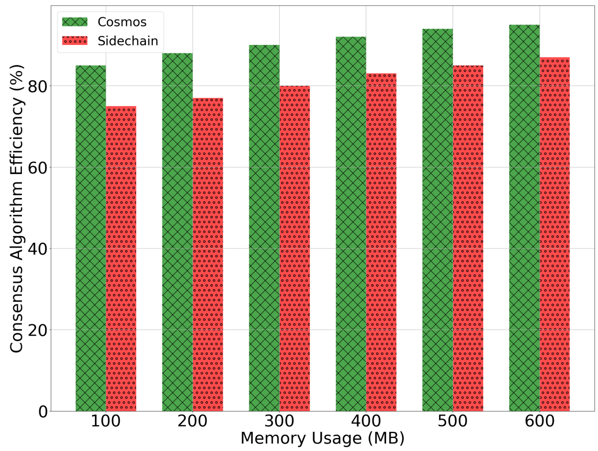

FIGURE 15. Comparison of consensus algorithm efficiency between cosmos and sidechain networks for different memory usage (MB).

layer, a multi-chain communication layer, and an application layer. The paper also introduced the model for packaging transactions and routing. Mohanty et al. [97] have shown an approach that used Delegated Stake-PBFT consensus. This enterprise blockchain architecture allows multiple chains to connect using a centralized protocol that enables cross-chain communication. The proposed router was formed as an Artificial Neural Network Chain (ANNChain) combined with other chain systems.

D. INDUSTRIAL SOLUTIONS: NETWORK OF BLOCKCHAINS

We also need to consider the industry-ready solutions that have evolved from sidechains and smart contracts and are now present before us in the form of actual systems solutions. The Polkadot project [98] is used for heterogeneous blockchains. In this project, the chosen token is Dot. The structure of Polkadot revolves around three primary categories: Parachains, Relay chains, and Bridges. Parachains function as diverse blockchains, relay chains oversee transaction consensus and delivery, and bridges connect parachains to their consensus. Within the Polkadot network, participants can take on one of four roles: Validators, nominees, Collators, or Fishermen. Using its platform, the ICON Project fosters connections among various blockchain entities and communities, including financial institutions, government offices, hospitals, and universities. This platform comprises Nexus and ICON Republic. Nexus is a collection of independent blockchain entities linked through ICON Republic portals [99]. ICON employs Loop Fault Tolerance (LFT) as its consensus algorithm, and its official token is ICX. LFT enhances BFT consensus algorithms using tendermint [100]. A notable constraint of the project is its specific focus and design tailored for Korea, aligning with the regulatory policies governing blockchain and crypto companies in the country [101]. Table 8 shows the ratio between the circulating supply and the total supply of tokens in all the above-mentioned chains. *Circulating Supply* refers to the number of tokens currently participating in transactions. The *Total Supply* refers to the total number of a specific cryptocurrency's coins or tokens in circulation on a blockchain and publicly available for the market to trade. We can see that even in its initial form, the Cosmos blockchain has a ratio of 1 as compared to other chains, depicting a complete adoption rate and resilience in the total amount of tokens produced. And thus, a viable solution. Block Collider [103] is a multi-chain platform built on a group of existing exported blocks from other blockchains in the network, integrating the chains to provide cross-chain features. Peer-to-peer decentralized miners collect the block from the connected blockchains with no centralized validators. Block collider uses a proof of distance consensus mechanism, a modified version of the proof of work consensus algorithm. The Aion Project [39] sets out to facilitate communication and foster cross-chain interoperability among various blockchain platforms. The Aion architecture forms a multi-tier blockchain network with four key components: Connecting Networks, Interchain Transactions, Bridges, and Participating Networks. Connecting Networks serve as protocols enabling different and independent blockchains to communicate within the AION Platform. Interchain transactions facilitate data transfer

TABLE 7. Comparison of blockchain interoperability solutions.

Feature / Study	Cosmos	Polkadot	ICON	AION
Consensus Mechanism	Tendermint	Nominated Proof-of-Stake (NPoS)	Loop Fault Tolerance (LFT)	Byzantine Fault Tolerance (BFT)
Interoperability Protocol	IBC	Cross-Chain Message Passing (XCMP)	Blockchain Transmission Protocol (BTP)	AION Interchain Communication (AIC)
Native Token	Atom	DOT	ICX	AION
Scalability	High, due to Tendermint and IBC	High, through parachains	Moderate, focuses on connecting multiple blockchains	High, designed for connecting enterprise blockchains
Transaction Finality	Instantaneous	Near-instantaneous	Instantaneous	Near-instantaneous
Governance	Decentralized, via Atom token holders	Decentralized, via DOT token holders	Decentralized, via ICX token holders	Decentralized, via AION token holders
Security	High, due to Tendermint's BFT	High, due to NPoS and shared security	High, due to LFT and multi-sig features	High, due to BFT and interchain transactions
Use Cases	Cross-chain asset transfers, decentralized finance (DeFi)	Cross-chain asset transfers, DeFi	Cross-chain asset transfers, DeFi	Cross-chain asset transfers, enterprise applications
Ecosystem Growth	Rapid, supported by various projects and active development	Rapid, with strong community and parachain projects	Moderate, growing steadily	Emerging, focusing on enterprise and cross-chain applications
Strategic Importance	High, revolutionizing blockchain interoperability and governance	High, strong emphasis on interoperability and scalability	Moderate, enhancing connectivity among blockchains	Moderate, providing enterprise solutions and interchain transactions

TABLE 8. Circulating supply to total supply ratio of various cross-chain platforms.

Platform	Circulating Supply	Consensus
ChainLink	0.58709997	Similar to PBFT
PolkaDOT	0.913973639	Proof-of-Stake
Stellar	0.570739823	Proof-of-Authority
ICON	0.9999999	Mimblewimble
Cosmos blockchain	1	PBFT

between connected blockchains within the ecosystem [50]. Bridges, a group of validators, validate these interchain transactions. Any blockchain network can become a Participating Network if it meets specific requirements defined by the Aion ecosystem. The consensus algorithm employed by the Aion ecosystem is a hybrid staking and proof-of-intelligence system. The native token of the Aion blockchain is called AION [104]. Metronome is a project that aims to create a better cryptocurrency solution by enhancing current cryptosystems. Along with enhancing the throughput, Metronome enables cross-blockchain transfer, where a user can transfer its token from one blockchain to another using a proof-of-exit receipt. The token used in this project is the Masternode Token Network (MTN). Ripple introduced the Interledger Protocol (ILP), a framework to facilitate atomic swaps between diverse blockchain platforms [49]. Unlike a blockchain platform, the Interledger protocol does not necessitate a consensus mechanism. Instead, it enables secure transactions without being tied to a specific blockchain. The protocol ensures sender and receiver isolation, mitigating risks associated with intermediary failures. Security in the transfer process is maintained through hash locking, wherein the payment is conditionally locked until the transfer is successfully secured. Figure 16 shows how the number of transfers has varied over a year. This trend is shown between a time of one year (Horizontal Axis) and the total number of tokens transferred in multiples of 1000 (Vertical Axis). Both trends show an increase in the total transfer counts, which is fairly high from December 2023. This shows how the adoption of the Cosmos blockchain has increased for first-time and regular users. It also highlights the number of senders and receivers on the Cosmos blockchain over the years. This also portrays the Cosmos blockchain's consistent behavior. The trend is shown between a time of one year (Horizontal Axis) and the number of tokens transferred (Vertical Axis). The steady increase in these trends is not a spike but a composition of variations with an overall increase. New chains joining the network are being sustained and remain stable. There are three data points colored with blue, green, and orange. Green represents the unique receivers, orange represents unique senders, and blue represents the total number of unique users on the chain. The transactions using blockchain being personalized and anonymized gives consumers the power to use it according to their convenience [105].

E. ANALYSIS BASED ON SWOT

Cosmos blockchain has a lot to offer. It is not a different kind of blockchain. Instead, it is an extension or an evolution of blockchain as a domain [95]. For a system relying on blockchain for its security, there will be a time when a cross-network request needs to be sent, or a data transfer needs to be made [106]. This is where an inter-chain network will come into use. For that, it is not just about the presence of a solution but also the functionality these systems will require. A high-performance and reliable system is always easier to adopt and use. This also builds consumer trust if it is in the form of a product [107]. Cosmos blockchain delivers on these parameters to the best extent. The flexibility with distributed governance and interoperability makes it a viable candidate for a cross-chain solution [12].

i. *Scalability*: The Cosmos blockchain ecosystem's focus on scalability through the use of Tendermint BFT consensus and the IBC protocol could enable the development of high-performance blockchain applications

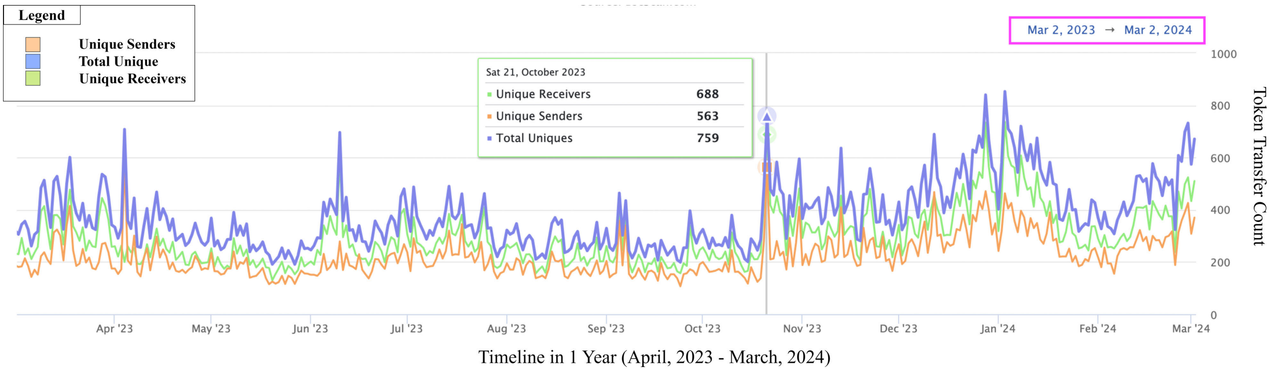

FIGURE 16. Cosmos blockchain transfer count over one year [102].

that can handle large transaction volumes and support a wide range of use cases.

ii. *Governance*: The Cosmos blockchain ecosystem's governance mechanisms, including those at the hub and zone levels, present an opportunity to develop more inclusive and democratic decision-making processes. This could lead to the creation of more community-driven blockchain applications and services.

iii. *Interoperability*: The Cosmos blockchain ecosystem's focus on interoperability between different blockchain networks presents a significant opportunity to develop cross-chain applications and services. The ability to transfer value and data seamlessly between different blockchain networks could unlock new use cases and business models.

iv. *Modular Architecture*: The Cosmos blockchain SDK is modular, allowing developers to customize and assemble various modules to create blockchain applications tailored to their specific use cases. This modular approach provides flexibility and extensibility, enabling developers to build applications with the desired functionality.

1) COSMOS DEVELOPMENT OPPORTUNITIES

Cosmos offers many development opportunities for those interested in blockchain. Its unique design allows different blockchains to work together, making creating new decentralized applications and services easier [95]. The growing community encourages collaboration and invites developers to contribute to open-source projects, providing a great platform for improving skills and building useful solutions. The following explores specific areas within Cosmos where developers can exploit these opportunities.

i. *Partnership:* Building of two or more services can be done by keeping the Cosmos blockchain as a platform. It can act as a platform that lays common rules in the form of a protocol so that different kinds of blockchains can communicate with each other, similar to the World Wide Web (WWW) that connects different devices, networks, and data centers by bringing them on the same platform, irrespective of the end-user platform, whether it is a laptop, smartphone, smart TV. The same tokens are accessible everywhere through a common channel.

ii. *Customized:* Another major area for the Cosmos blockchain to become a viable application is customized solutions for a network of blockchains. Customization is a major opportunity for the Cosmos blockchain to flourish since it has smaller individual blockchains in the form of zones that can have their own custom rules and mechanisms.

iii. *Independent Networks:* This leads us to another possibility of the Cosmos blockchain in independent private networks. This is very suitable for smaller consumers just starting to use blockchain as a security solution and want only specific features.

2) LIMITATIONS OF THE COSMOS BLOCKCHAIN

There are a few places where the Cosmos blockchain falls short and might showcase its weaknesses that are sometimes not in its full control, but surely, some measures can be taken to mitigate them.

1) *Smart Contract Vulnerabilities:* Smart contracts are an essential component of many blockchain applications, including those built on the Cosmos blockchain. Attackers could exploit the vulnerabilities in smart contracts to steal funds or compromise the network's security.
2) *Network Infrastructure Attacks:* The infrastructure that supports the Cosmos blockchain, including nodes and validators, could be targeted by attackers seeking to disrupt the network or compromise its security.
3) *Governance Attacks:* The governance mechanisms within the Cosmos blockchain ecosystem, including those at the hub and zone levels, could be targeted by attackers seeking to manipulate decision-making processes or compromise the network's security.

VII. USE CASES AND APPLICATIONS

Some effective and real-life applications are listed below that will help understand the potential of cross-chain

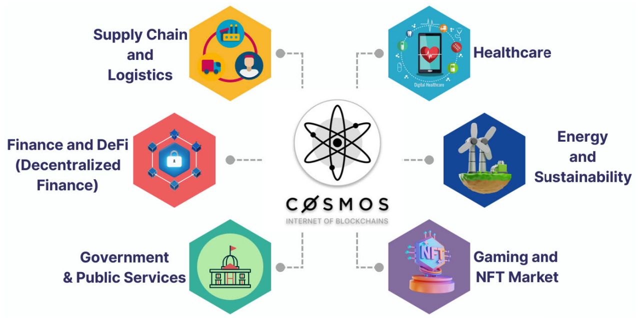

FIGURE 17. Application of cosmos blockchain in different aspects of society.

communication. Figure 17 will help illustrate this further by describing various aspects of society where the Cosmos blockchain finds its application.

A. IDENTITY MANAGEMENT

There are several places where organizations are in contact with employees of other organizations. The identity credentials of these employees are difficult to track and manage. Even in a large organization, many sub-organizations may host several people working and communicating with different teams. This can be facilitated and monitored with the help of Cosmos blockchain [63].

B. CENTRAL BANKING DIGITAL CURRENCY (CDBC)

Currently, there are studies on CBDC with a blockchain-based distributed ledger. This paper proposes Cosmos blockchain-based CBDC (Cos-CBDC), which enables communication between blockchains using the IBC protocol to ensure interoperability. We analyze the requirements of Cos-CBDC and design and implement it using Cosmos blockchain-SDK. The group of key management systems for Cos-CBDC gives different user privileges, and privacy-preserving is possible in the key generation process [108].

C. PROTECTION OF LIQUIDATION

Cross chains can help protect positions held in DeFi protocols across multiple chains by automatically sending assets from one chain to DeFi protocols on another to prevent liquidations [109]. With Industry 4.0 standards, data protection is being given more importance than ever. New Quantum-based solutions are emerging for data protection [40].

D. ETHEREUM AND BITCOIN TRANSACTIONS

The current technologies through which you store and transfer your Ethereum and Bitcoins are done through Cross-Chain communication. Polkadot and Chainlink tokens can manage most of this [110]. Wormhole and other non-token solutions should also get the job done, keeping more data on your device and less in the cloud [111].

E. GAMING

Cross-Chain by ChainLink allows gamers playing on a chain to interact with gamers on another chain. It enables interoperability between Web3 games across networks [112].

VIII. FUTURE WORK

Exploring the Cosmos blockchain's potential in addressing global challenges presents a promising avenue for future research. In DeFi, the Cosmos blockchain stands to revolutionize financial ecosystems by fostering interoperability across diverse blockchains, thus enabling a more inclusive financial landscape. Solutions are being developed specifically for connected vehicles that use blockchain as their communication medium [113]. The implications for supply chain management are equally transformative, with the Cosmos blockchain poised to enhance transparency and efficiency through blockchain integration, potentially reshaping global logistics. Transport and logistics, the way we currently travel by roads, is bound to be transformed by the internet of vehicles [114]. Cosmos blockchain could be instrumental in unifying medical records in healthcare, thereby improving patient care and accelerating research collaboration. The digital identity and authentication domain could also see a paradigm shift with the Cosmos blockchain, offering a secure and private identity management framework. The unfinished point on climate change and sustainability suggests a research trajectory where the Cosmos blockchain could support environmental initiatives, possibly through tracking carbon footprints or facilitating green economies. Each of these areas not only represents a significant stride in their respective fields but also underscores the multifaceted capabilities of the Cosmos blockchain as a tool for innovation and societal advancement.

IX. CONCLUSION

This paper explored various blockchain interoperability solutions, focusing on the Cosmos blockchain and its innovative approach to cross-chain communication. By exploring the Tendermint consensus mechanism and IBC protocol, Cosmos facilitates secure and scalable interactions between independent blockchains, addressing key limitations of isolated blockchain systems. The paper highlighted Cosmos's strengths, including its decentralized governance model and modular architecture, allowing flexible upgrades and customized blockchain applications. These features make Cosmos highly adaptable for use in industries such as finance, healthcare, gaming, and supply chain management, where secure cross-chain transactions are crucial. Despite these strengths, the paper also acknowledged challenges such as potential security vulnerabilities and architectural complexity that require further research. Cosmos presents a promising framework for the future of blockchain technology, with its scalability and decentralized approach positioning it as a key player in fostering blockchain interoperability. While there are areas for improvement, particularly in security, Cosmos has the potential to drive the evolution of decentralized applications and enable a more interconnected blockchain ecosystem.

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