Blockchain interoperability: challenges and solutions for a connected future

Mohammed A. Saleh[1,†], Saule Amanzholova[2,†], Zhibek Zhetekbay[1,†], Meruyert Dauletbek[1,†] and Ali Abd Almisreb[1,†]

[1] *International Information Technology University, 34/1 Manas St., 050000, Almaty, Kazakhstan*
[2] *Astana IT University, Astana, Kazakhstan*

Abstract

Blockchain technology has been increasingly popular in recent years, and many different platforms have emerged to meet specific needs. However, the inability of these platforms to work together smoothly prevents data and value from being easily exchanged, limiting the technology's full potential. This research paper explores the challenges and solutions related to blockchain interoperability and emphasizes its importance in building a more interconnected future. We will start by looking at the complexities of blockchain interoperability, including technical differences, security issues, and governance challenges. Then, we will examine various solutions, such as cross-chain protocols and interoperability frameworks, while pointing out their strengths and limitations. This paper explores how blockchain interoperability can be beneficial in industries like supply chain management, healthcare, and finance. Lastly, we will discuss upcoming trends, research areas, and the potential for blockchain interoperability to transform how we interact and conduct transactions in a decentralized world.

Keywords

Interoperability, Cross-Chain, DeFi, Emerging Tech, Challenges & Solutions

1. Introduction

With its decentralized, transparent, and secure features, blockchain technology has emerged as a revolutionary force that has the potential to completely disrupt a number of industries [1]. A blockchain is essentially a decentralized and tamper-proof ledger that securely records transactions on a network of interconnected computers, effectively removing the necessity for a centralized governing body.[2]. The underlying structure supports trust, transparency, and accountability, making it well-suited for various applications such as cryptocurrencies and supply chain management[3][4]. The widespread adoption of various blockchain platforms, each offering distinct features and capabilities, has led to a major obstacle: interoperability.

The absence of smooth communication and data transfer between diverse blockchains impedes the technology's full potential, resulting in isolated ecosystems that restrict scalability and innovation. This research paper provides an in-depth analysis of blockchain interoperability, focusing on the technical challenges and potential remedies for achieving seamless integration. We offer a thorough examination of fundamental concepts, emphasize the criticality of interoperability in unleashing the full potential of blockchain, and scrutinize both technical and non-technical obstacles impeding its advancement. In addition, we will explore current and developing solutions, assess their advantages and drawbacks, and consider how they could affect various industries. This paper seeks to offer valuable perspectives on the changing field of blockchain interoperability and its significance for a decentralized world by using practical case studies and analyzing future trends.

DTESI 2024: 9th International Conference on Digital Technologies in Education, Science and Industry, October 16–17, 2024, Almaty, Kazakhstan
* Corresponding author.
† These authors contributed equally.
mohamedswm@yahoo.com (M. Saleh); s.amanzholova@astanait.edu.kz (S. Amanzholova); alimes96@yahoo.com (A. Almisreb)
0000-0002-6779-9393 (S. Amanzholova); 0000-0001-7581-5747 (A. Almisreb)

1.1 Background

The interoperability market is projected to reach USD 1.0 billion by 2028, growing at a CAGR of 27.2% during the forecast period. Figure 1 illustrates the Global Forecast for the Blockchain Interoperability Market up to 2028.

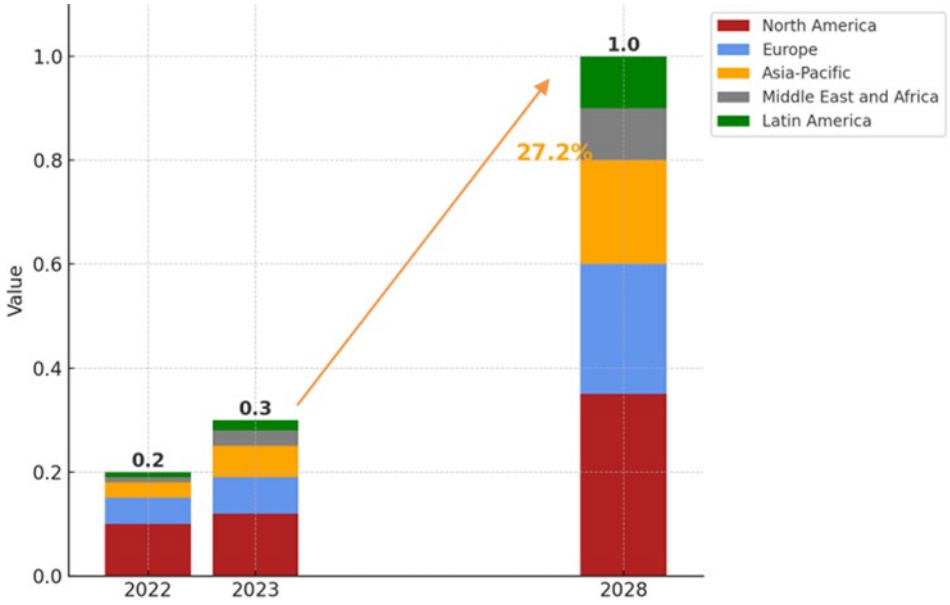

Figure 1: Blockchain Interoperability Market Global Forecast To 2028 (USD Billion) [5].

1.2 Definition of interoperability in blockchain

Interoperability in the context of blockchain technology pertains to the capacity of distinct blockchain networks to seamlessly communicate and exchange data. This involves a range of elements, such as:

- Syntactic Interoperability: The capacity of several blockchains to relate to the protocols and data formats of one another [6];
- Semantic Interoperability: The capacity to understand and make meaningful use of the data transmitted across many blockchains [6];
- Functional Interoperability: The ability of various blockchains to process transactions and execute smart contracts across their networks.[7].

1.3 Current state of blockchain networks

In the current blockchain landscape, there are a multitude of independent platforms, each with its own strengths and limitations. While diversity fosters innovation, it also results in fragmentation, hindering the flow of data and value across ecosystems [8] [9] [10]. There are a number of challenges associated with this lack of interoperability, including:

- Limited Scalability: Isolated blockchains struggle to handle the increasing volume of transactions required for widespread adoption.
- Restricted Functionality: The inability to interact with other blockchains limits the development of complex decentralized applications (dApps) that leverage the strengths of multiple platforms.
- Siloed Data: Data stored on separate blockchains remains inaccessible to other networks, hindering collaboration and innovation.

1.4Examples of interoperability efforts

The importance of interoperability is recognized by a variety of initiatives and projects aimed at connecting different blockchain networks. The following are some noteworthy examples:

- Cosmos: A decentralized network of independent blockchains connected through a standardized communication protocol, enabling interoperability and scalability [6].
- Polkadot: A multi-chain framework that allows for the creation of interconnected blockchains, facilitating cross-chain communication and data sharing [11].
- Chainlink: A decentralized oracle network that provides real-world data to blockchains, enabling the development of more sophisticated and interconnected dApps [12].

In addition to highlighting the growing momentum behind blockchain interoperability, these efforts show its potential for unlocking new decentralized applications.

2. Challenges in blockchain interoperability

Although blockchain interoperability offers significant potential benefits, it faces various challenges that need to be addressed for full realization. These challenges fall into three main categories: technical, security, and governance and regulatory aspects [12].

From a technical standpoint, the diversity of blockchain platforms in terms of their architectures, consensus mechanisms, and data structures presents a complex challenge for achieving interoperability. Solutions for interoperability must be capable of managing the increasing volume of transactions and data exchange between blockchains without sacrificing performance. Moreover, establishing common data formats and ensuring consistent data interpretation across different blockchains is essential for meaningful interoperability [13].

Regarding security, interoperability solutions introduce new risks, as vulnerabilities in one blockchain could potentially compromise the security of interconnected chains. Sharing data across different blockchains also raises concerns about data privacy and confidentiality, particularly when handling sensitive information. Ensuring the secure and reliable execution of smart contracts across different blockchain platforms with varying programming languages and execution environments poses a significant challenge [10].

On the governance and regulatory front, the lack of widely accepted standards and protocols for blockchain interoperability impedes the development of interoperable solutions and leads to fragmentation. The evolving regulatory landscape surrounding blockchain technology creates uncertainty for developers and businesses looking to implement interoperability solutions. Achieving interoperability often necessitates collaboration among various stakeholders, including blockchain developers, businesses, and regulators, across different jurisdictions, which can be intricate and time-consuming[9].

2.1 Technical challenges

Interoperability is complicated by the differences in blockchain architectures, consensus mechanisms, and data structures. Effective solutions must also address the growing data exchange between blockchains while ensuring high performance. Furthermore, real interoperability cannot be achieved without defining standard data formats and guaranteeing consistent data interpretation across several blockchains [14].

2.2 Security concerns

Introducing interoperability solutions brings about new security concerns, because vulnerabilities in one blockchain could potentially jeopardize the security of interconnected chains. The sharing of

data across different blockchains gives rise to worries regarding data privacy and confidentiality, particularly when handling sensitive information. It is a significant challenge to guarantee the secure and dependable execution of smart contracts across diverse blockchain platforms with different programming languages and execution environments.[15] [16] [17].

2.3 Governance and regulatory challenges

There is a lack of widely accepted standards and protocols for blockchain interoperability, which hinders the development of interoperable solutions. Developers and businesses seeking interoperability solutions face uncertainty as the regulatory landscape around blockchain technology evolves. Blockchain interoperability requires collaboration among different stakeholders, including blockchain developers, businesses, and regulators, across different jurisdictions, which can be incredibly complex and time-consuming [18], [19].

3. Solutions for blockchain interoperability

Various solutions are being developed and implemented to overcome the challenges hindering blockchain interoperability:

3.1 Cross-chain protocols

Cross-chain protocols facilitate direct communication and asset transfers between different blockchain networks. They typically involve creating a communication layer to translate messages and transactions between the participating blockchains. Examples include:

- Inter-Blockchain Communication: Used by Cosmos, IBC allows independent blockchains to interact and exchange data securely [20].
- XCMP: Polkadot's protocol for enabling communication between parachains (parallel blockchains) within its ecosystem [21].

3.2 Interoperability frameworks

Interoperability frameworks offer a standardised architecture and a set of tools for creating interoperable blockchain applications, aiming to streamline the development process and foster interoperability between different platforms. Examples include:

- Cosmos SDK: A software development kit for building interoperable blockchains that can connect to the Cosmos Hub and other IBC-enabled chains [21].
- Substrate: Polkadot's framework for building customized blockchains (parachains) that can interoperate within the Polkadot ecosystem [22].

3.3 Decentralized bridges

Decentralized bridges play a crucial role in connecting different blockchains by acting as intermediaries. They facilitate communication and enable the transfer of assets between blockchains without the need for a central authority. Typically, these bridges involve locking assets on one blockchain and creating equivalent tokens on another blockchain. This mechanism allows for seamless and secure cross-chain transactions, further enhancing interoperability across different blockchain networks and ecosystems. Examples include:

- Wrapped Bitcoin: An ERC-20 token on Ethereum that represents Bitcoin, allowing Bitcoin holders to participate in DeFi applications on Ethereum [23].
- RenVM: A decentralized protocol that enables the creation of wrapped tokens for various assets, facilitating their use across different blockchains [24].

3.4 Interoperability standards

Establishing common standards and protocols is crucial for achieving widespread blockchain interoperability. Standardization efforts aim to define common data formats, communication protocols, and security measures, making it easier for different blockchains to interact seamlessly. Some notable initiatives include:

The World Wide Web Consortium Blockchain Community Group is working on developing standards and best practices for blockchain technology, including interoperability. The Enterprise Ethereum Alliance is focusing on driving the adoption of Ethereum-based technologies, including interoperability solutions for enterprise use cases. These solutions, both individually and collectively, are paving the way for a more interconnected blockchain ecosystem, unlocking new possibilities for colla boration, innovation, and value creation [19].

4. Case studies

Blockchain services vary widely, depending on the level of modernization and the governance structure in place. Here, we present two use cases. Figure 2 illustrates the interoperable services in the Cosmos Network, showing how multiple blockchains can connect through a standardized communication protocol to exchange data and assets securely.

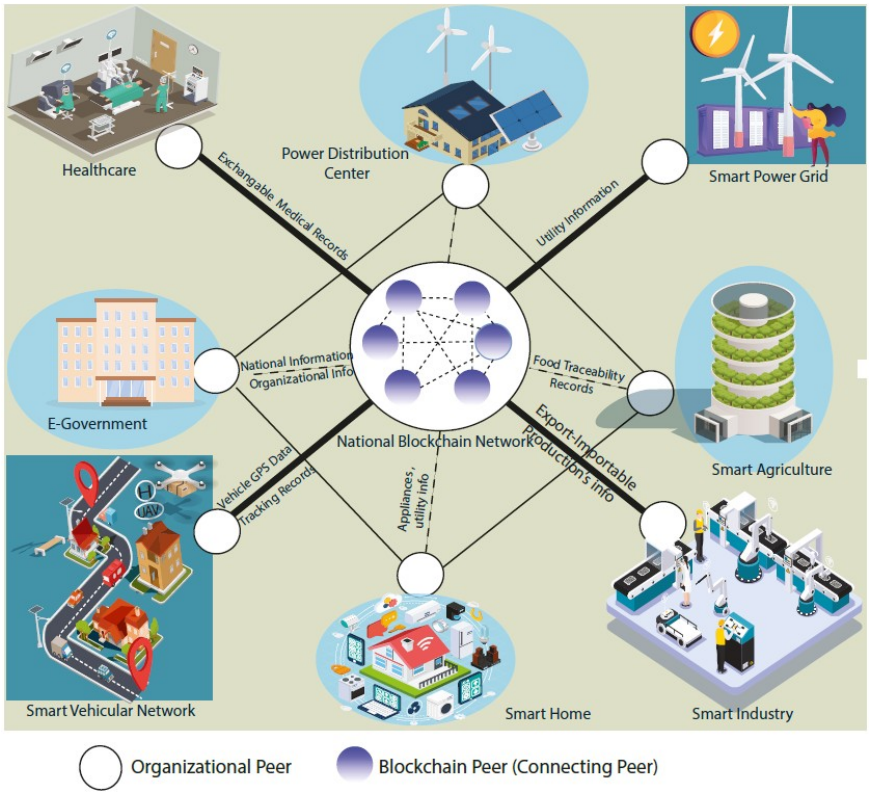

Figure 2: Blockchain Interoperability of Services [25].

4.1 Case study1: cosmos network - a successful interoperability project

The Cosmos Network stands as a prime example of a successful interoperability project, effectively addressing key challenges and achieving significant outcomes in the blockchain space.

Cosmos aims to create an "Internet of Blockchains," where diverse, independent blockchains can seamlessly interact and exchange value. It achieves this through a combination of innovative technologies:

Tendermint BFT is a high-performance, Byzantine fault-tolerant consensus mechanism that ensures fast and secure transaction processing. The Cosmos SDK is a modular framework that

simplifies the creation of application-specific blockchains, called "zones," which can easily connect to the Cosmos Hub. Inter-Blockchain Communication is a standardized protocol that enables secure communication and asset transfers between connected blockchains [26].

4.1.1 Addressing challenges

Cosmos tackles several key interoperability challenges. It accommodates the diversity of blockchain platforms by allowing zones to maintain their own governance and technical specifications. Additionally, the hub-and-zone architecture, coupled with Tendermint BFT, enables high transaction throughput and scalability. Furthermore, each zone maintains its own security, while IBC ensures secure communication and asset transfers between chains.

4.1.2 Outcomes achieved

The Cosmos Network has achieved notable success. It boasts a thriving ecosystem of interconnected blockchains, including projects like Binance Chain, Terra, and Kava. Cosmos-based blockchains power various real-world applications, from decentralized finance to supply chain management and gaming. Additionally, the Cosmos SDK has gained significant traction among developers, simplifying the creation of interoperable blockchains [27].

The Cosmos Network demonstrates the feasibility and potential of blockchain interoperability. By addressing key challenges and fostering a vibrant ecosystem, Cosmos paves the way for a more interconnected and collaborative blockchain future.

4.2 Case study

While the Cosmos Network showcases successful interoperability, it's crucial to analyze projects facing significant hurdles to glean valuable lessons. One such example is the Polkadot Parachain Slot Auction process.

4.2.1 Challenges faced

While innovative, the Polkadot parachain auction system has encountered several notable challenges. The high barrier to entry, created by the requirement to lock up a significant amount of DOT, poses difficulties for smaller or newer projects that may lack the necessary resources. This can potentially hinder innovation and limit participation from a diverse range of projects. Additionally, the complexity of the auction process and the competitive nature of the system can lead to overbidding and resource constraints within the Polkadot ecosystem. Finally, the initial selection of parachains through a governance process has raised concerns about potential centralization and favoritism, as the decentralized vision of the platform may not have been fully realized in practice. The parachain auction system has encountered challenges:

- High Barrier to Entry: The auction process requires projects to lock up a significant amount of DOT, creating a high barrier to entry, especially for smaller or newer projects. This favors well-funded projects and potentially hinders innovation from smaller players.
- Complexity and Competition: The auction process is complex, requiring specialized knowledge and resources. The competitive nature can lead to overbidding and potential resource constraints within the Polkadot ecosystem.
- Centralization Concerns: While designed to be decentralized, the initial selection of parachains involved a governance process that raised concerns about potential centralization and favoritism [23].

4.2.2 Lessons learned

The Polkadot parachain auction experience offers valuable lessons. It highlights the need to balance securing the network through high-stakes auctions with ensuring accessibility for a diverse range of projects, which is crucial for a thriving ecosystem. Transparent auction rules and a fair selection process are essential for building trust and encouraging participation from a wider range of projects. Furthermore, active community involvement in governance and decision-making processes can help mitigate centralization risks and ensure the platform's long-term health.

Polkadot's experience highlights the complexities of balancing security, decentralization, and accessibility in blockchain interoperability. It underscores the need for ongoing innovation in auction mechanisms, governance models, and community engagement to create a more inclusive and robust interoperable blockchain ecosystem [23].

5. Future trends and research directions

The field of blockchain interoperability is constantly evolving, with new technologies and approaches emerging to address existing challenges and unlock new possibilities. Here are some key trends and research directions shaping the future of blockchain interoperability.

5.1 Emerging technologies

Blockchain interoperability is driven by the rapid development of emerging technologies that aim to overcome the siloed nature of individual blockchain networks. These cutting-edge innovations hold the potential to unlock new possibilities for cross-chain collaboration and value creation. Let's explore some of the key emerging technologies shaping the future of blockchain interoperability.

- Layer-2 Scaling Solutions: Solutions like state channels and rollups, initially developed for scaling individual blockchains, are being explored for their potential to enhance interoperability. By moving transactions off-chain, these solutions can improve throughput and reduce costs for cross-chain communication.
- Zero-Knowledge Proofs: ZKPs allow one party to prove the validity of a statement to another party without revealing the underlying data. This technology has significant implications for interoperability, enabling the verification of transactions and data across different blockchains without compromising privacy or security.
- Trusted Execution Environments: TEEs are secure enclaves within a device's processor that can execute code and handle data in a trusted and isolated environment. TEEs can enhance interoperability by providing a secure and standardized way for different blockchains to interact and share data [28].

5.2 Evolving standards

- Decentralized Identifiers: DIDs provide a standardized way to represent digital identities on blockchains, enabling interoperable identity management and authentication across different platforms.
- Verifiable Credentials: Building on DIDs, verifiable credentials allow for the issuance and verification of tamper-proof digital credentials, facilitating interoperable data sharing and trust between different entities.
- Cross-Chain Communication Protocols: Ongoing research and development efforts are focused on creating more efficient, secure, and standardized protocols for communication and data exchange between blockchains [29].

5.3 Opportunities for innovation

Enabling seamless interoperability between different DeFi protocols and platforms can unlock a wealth of new possibilities for composability, liquidity, and innovation in the decentralized financial services ecosystem. By fostering seamless cross-chain collaboration, interoperable DeFi solutions can facilitate the development of novel financial products, improve access to diverse liquidity pools, and enable innovative financial applications that leverage the unique capabilities of multiple blockchain networks.

Similarly, interoperable solutions for managing and sharing data across blockchains have the potential to revolutionize a wide range of industries, including supply chain management, healthcare, and identity verification. By enabling the secure and transparent exchange of data between different blockchain networks, these interoperable systems can enhance traceability, improve supply chain efficiency, facilitate the sharing of healthcare records, and streamline identity management processes, unlocking new opportunities for optimization and collaboration.

Furthermore, integrating blockchains with IoT devices and networks can significantly enhance security, transparency, and automation in various sectors, from supply chain tracking to smart cities. By leveraging blockchain's immutable ledger and consensus mechanisms, these interoperable systems can provide a trustworthy and tamper-resistant foundation for IoT-powered applications, enabling secure data exchange, automated workflows, and enhanced visibility across a wide range of industries and use cases.

6. Conclusion

Addressed to realise the full potential of blockchain technology. While significant progress has been made in developing innovative solutions like Polkadot's parachain auctions, numerous obstacles still need to be overcome. As the conclusion of this paper makes clear, blockchain interoperability is a critical challenge that must be addressed in order to realise the full potential of blockchain technology In conclusion of this paper, blockchain interoperability is a critical challenge that must be. While significant progress has been made in developing innovative solutions like Polkadot's parachain auctions, numerous obstacles still need to be overcome. Overcoming these challenges and achieving true blockchain interoperability will be essential for enabling seamless collaboration and data exchange across different blockchain networks, which in turn will unlock new opportunities for value creation and societal impact. This will require continued innovation, collaboration, and community engagement within the broader blockchain ecosystem. The key challenges include technical barriers, such as the need for standardised communication protocols and data exchange mechanisms, as well as governance and economic challenges, like ensuring fair and inclusive participation in interoperability platforms. Looking to the future, emerging technologies like zero-knowledge proofs, trusted execution environments, and evolving standards for decentralised identities and verifiable credentials offer promising avenues for advancing blockchain interoperability. As the blockchain ecosystem matures, a continued focus on innovation, collaboration, and community engagement will be crucial in creating a more connected, interoperable, and decentralised future.

Declaration on Generative AI

During the preparation of this work, the authors used X-GPT-4 in order to: Proofread the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication’s content.

References

[1] S. Thakur and V. Kulkarni, “Blockchain and Its Applications – A Detailed Survey,” Int J Comput Appl, vol. 180, no. 3, 2017, doi: 10.5120/ijca2017915994.

[2] R. Anascavage and N. Davis, “Blockchain technology: A literature review,” Available at SSRN 3173406, 2018, [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3173406.

[3] C. S. Wright, “Bitcoin: A Peer-to-Peer Electronic Cash System,” SSRN Electronic Journal, 2019, doi: 10.2139/ssrn.3440802.

[4] D. Yaga, P. Mell, N. Roby, and K. Scarfone, “Blockchain Technology Overview - National Institute of Standards and Technology Internal Report 8202,” NIST Interagency/Internal Report, 2018.

[5] “Blockchain Interoperability Market Size, Share and Global Market Forecast to 2028 | MarketsandMarkets.” Accessed: Aug. 18, 2024. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/blockchain-interoperability-market-25113202.html.

[6] K. M. K. and A. F. Jokhio, “Empirical Investigation on Blockchain Interoperability,” vol. 11, no. 1, pp. 25–36, Aug. 2023, doi: 10.21015/vtse.v10i4.1315.

[7] G. Llambías, L. González, and R. Ruggia, “Blockchain Interoperability: a Feature-based Classification Framework and Challenges Ahead,” CLEI Eletronic Journal (CLEIej), vol. 25, no. 3, 2023, doi: 10.19153/CLEIEJ.25.3.4.

[8] R. Belchior, A. Vasconcelos, S. Guerreiro, and M. Correia, “A Survey on Blockchain Interoperability: Past, Present, and Future Trends,” ACM Comput Surv, vol. 54, no. 8, pp. 1–41, Nov. 2022, doi: 10.1145/3471140.

[9] M. H. T. and R. V. Veeraragavan, “Understanding blockchain: definitions, architecture, design, and system comparison,” Aug. 2022. doi: 10.48550/arxiv.2207.02264.

[10] P. T. Tessone and Claudio J, “Ontology of Blockchain Technologies. Principles of Identification and Classification,” RELX Group (Netherlands), Aug. 2017, doi: 10.2139/ssrn.2977811.

[11] G. W.-W. paper and undefined 2016, “Polkadot: Vision for a heterogeneous multi-chain framework,” win.tue.nl, Accessed: Aug. 18, 2024. [Online]. Available: https://www.win.tue.nl/~mholende/seminar/references/ethereum_polkadot.pdf

[12] C. G. Harris, “Cross-Chain Technologies: Challenges and Opportunties for Blockchain Interoperability,” Aug. 2023, doi: 10.1109/coins57856.2023.10189298.

[13] D. Y. and P. M. Scarfone, “Blockchain technology overview,” Aug. 2018. doi: 10.6028/nist.ir.8202.

[14] H. J. X. D. Xiao, “Towards a Novel Architecture for Enabling Interoperability amongst Multiple Blockchains,” Aug. 2018, doi: 10.1109/icdcs.2018.00120.

[15] B. H. and Z. Z. Lin, “A comprehensive survey on smart contract construction and execution: paradigms, tools, and systems,” Aug. 2021. doi: 10.1016/j.patter.2020.100179.

[16] H. Taherdoost, “Smart Contracts in Blockchain Technology: A Critical Review,” Aug. 2023. doi: 10.3390/info14020117.

[17] S. T. and S. T. Skwarek, “Moving Smart Contracts – A Privacy Preserving Method for Off-Chain Data Trust,” Aug. 2022. doi: 10.48550/arxiv.2205.08440.

[18] “Digital Currency Governance Consortium White Paper Series,” Aug. 2023. [Online]. Available: https://www3.weforum.org/docs/WEF_Defining_Interoperability_2021.pdf.

[19] N. W. L. and Y. W. Hewett, “Inclusive Deployment of Blockchain for Supply Chains,” in World Economic Forum, Aug. 2019. [Online]. Available: http://www3.weforum.org/docs/WEF_A_Framework_for_Blockchain_Interoperability_2020.pdf.

[20] S. J. and P. R. Brainard, “Sidechains and interoperability,” Aug. 2019. doi: 10.48550/arxiv.1903.04077.

[21] C. Goes, “The Interblockchain Communication Protocol: An Overview,” Jun. 2020, Accessed: Aug. 18, 2024. [Online]. Available: https://arxiv.org/abs/2006.15918v1

[22] D. R. and A. H. M. Datta, “PIEChain – A Practical Blockchain Interoperability Framework,” Aug. 2023. doi: 10.48550/arXiv.2306.

[23] I. K. and A. G. Seneviratne, “Blockchain Interoperability Landscape,” Aug. 2022. doi: 10.48550/arXiv.2212.
[24] G. Caldarelli, “Wrapping Trust for Interoperability: A Preliminary Study of Wrapped Tokens,” Multidisciplinary Digital Publishing Institute, vol. 13, no. 1, p. 6, Aug. 2021, doi: 10.3390/info13010006.
[25] S. Biswas et al., “Interoperability Benefits and Challenges in Smart City Services: Blockchain as a Solution,” Electronics (Switzerland), vol. 12, no. 4, Feb. 2023, doi: 10.3390/electronics12041036.
[26] E. B. and J. H. K. Milošević, “The latest gossip on BFT consensus,” Aug. 2018. doi: 10.48550/arxiv.1807.04938.
[27] C. J. and C. W. Bach, “Blockchain Technology and Cryptocurrencies: Opportunities for Postal Financial Services,” Aug. 2017. doi: 10.1007/978-3-319-46046-8_13.
[28] “Board of Governors of the Federal Reserve System,” Association of College and Research Libraries, vol. 37, no. 12, pp. 37Sup – 463, Aug. 2000, doi: 10.5860/choice.37sup-463.
[29] W. J. G. and A. Agrawal, “Blockchain Technology for Healthcare: Facilitating the Transition to Patient-Driven Interoperability,” Aug. 2018. doi: 10.1016/j.csbj.2018.06.003.