Available online at www.HighTechJournal.org

HighTech and Innovation Journal

ISSN: 2723-9535

Vol. 4, No. 4, December, 2023

Enhancing Trustworthiness and Interoperability of Electronic Voting Systems through Blockchain Bridges

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Received 03 September 2023; Revised 15 November 2023; Accepted 19 November 2023; Published 01 December 2023

Abstract

Decentralized applications leveraging blockchain technology are gaining widespread adoption within the decentralized applications ecosystem. Interoperability, a fundamental concept facilitating seamless data and processing power exchange across diverse blockchain networks, is paramount in this context. The primary objective of this paper is to explore the transformative potential of "blockchain bridges" in facilitating secure and transparent electronic voting processes across multiple blockchain networks. The study employs a comprehensive analysis of various approaches, including atomic exchanges, sidechains, cross-chain bridges, token wrappers, and interledger protocols. The selection of a specific method is guided by the unique requirements and privacy considerations of the electronic voting use case. The application of two distinct blockchains serves as a practical demonstration, illustrating the principles of blockchain bridges in real-world scenarios. The research reveals that blockchain bridges not only streamline the exchange of data between diverse blockchain networks but also establish a dual decentralization paradigm. This paradigm enables the creation of openly maintained, purpose-specific, decentralized ledgers for electronic voting. The integration of blockchain bridges significantly reduces the risk of fraud, instilling greater confidence in the accuracy of election results. Thus, by presenting a comprehensive array of approaches and emphasizing their practical application, this research contributes to advancing the understanding and implementation of blockchain technology in the critical domain of electronic voting.

Keywords: Blockchain; Bridge; e-Voting; Trustworthiness; Interoperability.

1. Introduction

Blockchain, a transformative technology, has transformed the way we transact, store, exchange, and manage data. This technology is a distributed ledger that creates a secure and immutable record of transactions on a shared network. It is a distributed digital ledger that securely records and verifies transactions across a network of computers. Distributed, in this case, means no central authority or server is required to manage the ledger. This eliminates the necessity for any middleman, enabling faster, more secure, and more efficient transactions. To elaborate, a blockchain is a chain of transaction blocks where each block in the chain contains a cryptographic hash of the previous block, i.e., a timestamp, and transaction data. This data is securely stored on the blockchain and accessible to anyone on the network.

Blockchain has been applied to several industries, with a notable impact on finance, where it provides a transparent and secure way of storing and transferring funds. Beyond finance, it is being applied to government functions, including

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http://dx.doi.org/10.28991/HIJ-2023-04-04-04

electronic voting and other services. The integration of blockchain into government services provides a robust mechanism for enhancing the transparency, effectiveness, and security of public services. However, obstacles concerning security and scalability may be present, including privacy and confidentiality issues, which must be considered and properly addressed. Voting, particularly electronic voting in this context, is a powerful tool that is crucial to determining the degree of democracy in a country. Therefore, integrating blockchain technology can enhance trustworthiness by ensuring that votes are stored securely, immutable, and verifiable. Additionally, blockchain technology creates immutable records of public services, secures and distributes government data, and rapidly completes secure transactions. Therefore, it is crucial for both citizens and governments to utilize the potential of blockchain technology to transform the voting process.

Among the various voting methods, online voting can achieve security, transparency, and efficiency by using blockchain-based voting systems. The incorporation of blockchain technology in electronic voting systems provides a more secure, accurate, and transparent platform. This approach also provides a cost-effective solution by reducing election expenses, making it an attractive and innovative option for practical voting procedures. Whether the ledger is public, mixed, or private, distributed ledger technology ensures that every vote is recorded on a secure, immutable ledger, making it extremely difficult for anyone to manipulate the vote outcome. Blockchain-based voting systems achieve accuracy due to their algorithms based on cryptography. These algorithms ensure that every vote is accurately cast and counted, eliminating the possibility of votes being lost or manipulated. Transparency is achieved since every vote is registered with a public, mixed, or private leader. This means anyone can audit the system and verify that the results are accurate and transparent. Election-related costs will be significantly reduced by using blockchain technology to achieve cost-effectiveness. This reduction comes from the fact that running a distributed ledger is significantly less expensive than running a traditional voting system. Overall, the implementation of blockchain technology in e-voting systems not only ensures heightened security, enhanced accuracy, and complete transparency but also paves the way for significant cost reduction, thus revolutionizing the voting process. The use of blockchain technology in electronic voting has been explored through various schemes, such as those using a single blockchain as well as those employing multiple blockchains or hybrid blockchains, as proposed by Neziri et al. [1].

In Chapter III of this paper, additional information and results will be presented and discussed, focusing on blockchain bridges in general and blockchain bridges in electronic voting, particularly. Blockchain technology can provide a secure, transparent, and immutable platform for electronic voting. Blockchain technology can create a tamper-proof and auditable ledger of all votes, allowing for a transparent and verifiable election process. However, to enhance the efficiency of blockchain-based electronic voting systems, multiple blockchains or a hybrid blockchain can be employed. Multiple blockchains, or hybrid blockchain solutions, are designed to enhance the accuracy and reliability of blockchain-based electronic voting systems. These solutions enable the integration of multiple blockchains with different features, such as scalability, security, and privacy, to create a more effective and robust network. By connecting multiple blockchains, the electronic voting system can leverage the strengths of each blockchain network, making it more reliable and effective. While there is a positive trend surrounding cross-chain or blockchain bridge technologies, it remains in its infancy [2], and there is still a lack of comprehensive studies that focus on the security, privacy, and effectiveness of inter-chain or interoperability technologies. This dearth emphasizes the need for comprehensive studies to examine these critical aspects, aiming to enhance our understanding and facilitate advancements in cross-chain functionalities.

Figure 1 represents the number of research articles per year for "blockchain bridge" that resulted from a Google Scholar search. In 2019, only two research documents were found regarding blockchain bridges. However, a considerable increase in interest has been observed in subsequent years. The search results showed a gradual increase, with figures of 6, 10, 32, and 38 for the years 2020, 2021, 2022, and 2023, respectively. This higher trend signifies a substantial focus in scholarly attention on this area of research. Blockchain bridges are a key component of connecting different blockchains within an electronic voting system. These bridges facilitate the interoperability of multiple blockchain networks, allowing users to transact across various blockchain networks. Blockchain bridges enable the transfer of assets or data between different blockchain networks without the need for a centralized intermediary. By utilizing blockchain bridges, electronic voting systems can provide more efficient transactions across multiple networks, allowing for faster and more secure voting processes. Additionally, blockchain bridges can increase the liquidity of the blockchain-based electronic voting system, as users can transact across multiple blockchain networks without any hassle. This can improve the efficiency and effectiveness of the electronic voting system, creating a more accessible and transparent voting process. Blockchain technology has been explored in electronic voting through multiple blockchains or hybrid blockchain solutions, which are connected through blockchain bridges. The concept of blockchain interoperability revolves around the essential requirement for distributed systems to establish communication channels with external third-party systems, all without the need for a single, canonical chain [3]. This principle emphasizes the necessity for multiple blockchain networks to seamlessly interact, exchange data, and function independently across distinct, independent systems without relying on a centralized authority or common infrastructure. The evolution of the blockchain into a blockchain ecosystem, or multi-chain environment with various blockchains claiming to be utilized, has led to the creation of bridges that facilitate asset transfers between these blockchains. This phenomenon is evident not only in electronic voting but also in academic institutions [4, 5], healthcare [6], and other areas [7, 8].

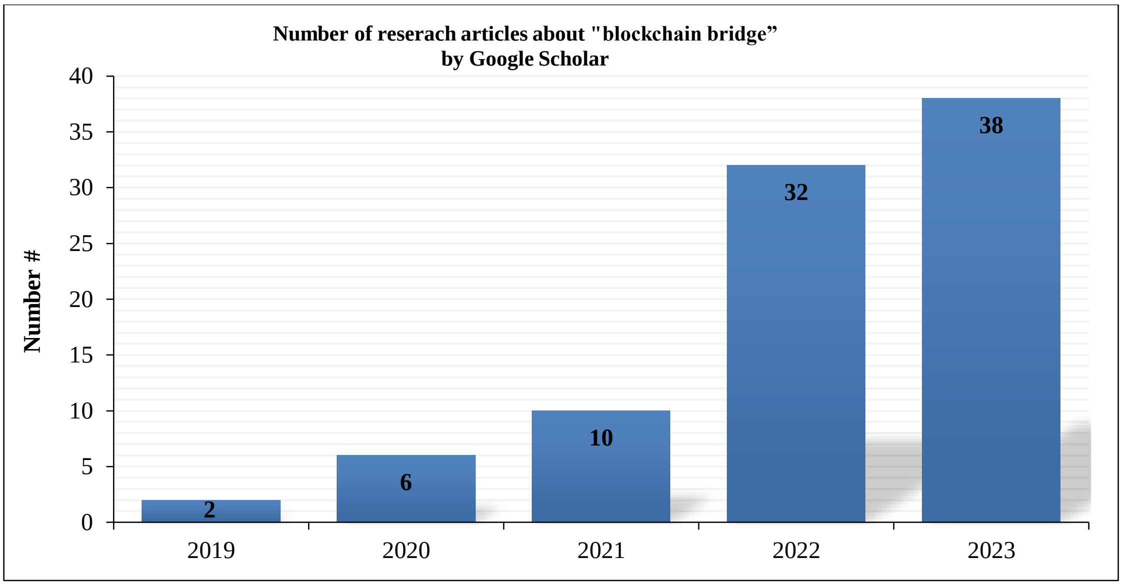

Figure 1. Research trends on blockchain bridge

Wegner introduced the concept of interoperability in 1996, defining it as "*the capacity of multiple software components to collaborate effectively despite the disparities in language, interface, and execution platform*" [9]. Wegner's work served as a bridge between the idea of interoperability and the prevailing standards of the time. As researchers explore the domain of blockchain interoperability, they are deeply influenced by the architectural framework and principles of the Internet. This perspective highlights the importance of studying the Internet's architecture as a means of comprehending the potential mechanisms for achieving blockchain interoperability in general and bridging in particular. The importance of addressing the challenge of blockchain interoperability becomes evident when considering its broader implications. The issue of blockchain interoperability is crucial due to its potential to unlock synergies between various blockchain solutions. This solves the issue by improving the scalability of current systems and promoting the creation of new applications, such as electronic voting.

The National Institute of Standards and Technology (NIST) elaborates on the concept of blockchain interoperability in a technical report, describing it as "the integration of distinct blockchain systems, each functioning as an independent distributed data ledger. In this context, atomic transactions can extend across multiple heterogeneous blockchain systems, while data recorded in one blockchain can be accessed, verified, and referenced by another, even if it originates from a foreign transaction, all within a semantically compatible framework" [11].

2. Blockchain Bridge

Blockchain interoperability requires seamless communication and data sharing between multiple blockchain systems. Interoperability strives to define a standard protocol that allows the exchange of information while preserving the autonomy of individual blockchains. The main issue remains the consensus of each chain and how data moves from one chain to another [12]. This overarching concept serves as a catalyst for the challenge of isolated blockchain networks by fostering collaborative functionality among them. Additionally, a blockchain bridge is a technical mechanism that is utilized to facilitate communication and data transfer between distinct blockchain networks. For example, consider an application that is hosted on the Ethereum blockchain that is connected to the EOS blockchain. This application can connect the capabilities of Ethereum's smart contracts while also benefiting from the scalability features offered by EOS. The seamless exchange of data, information, and tokens between these two blockchain platforms is achieved using blockchain bridges.

The bridge is a crucial element in ensuring the secure transfer of data while safeguarding the integrity and security of the exchanged information. A blockchain bridge is a tool or part of technology that allows interaction and communication between various blockchain networks. It allows for the transfer of digital assets and data between different blockchains, resulting in the creation of a seamless and interoperable ecosystem. Blockchain bridges employ various cryptographic protocols, consensus algorithms, and smart contracts that ensure the integrity and security of the data being transferred. They offer some advantages, including cross-chain transaction efficiency, security, and transparency. However, there are also issues such as scalability, interoperability, and regulatory issues that need to be addressed. According to Belchior et al. [13], it is essential to tackle the issue of blockchain interoperability and guarantee it between blockchains to leverage the strengths of diverse solutions, expand current ones, and create new use cases. During the early stages of blockchain research, interoperability was not considered necessary, as the primary focus was on dealing with issues [14, 15]. Despite these challenges, blockchain bridges possess great potential for creating a decentralized, interoperable future. The implementation and complexity of a blockchain bridge can vary significantly based on the specific use case, the blockchain platforms being connected, and the technology used to secure data transfer. Figure 2 shows a conceptual representation of how a blockchain bridge connects networks A and B. When a new block is added to Blockchain A (e.g., Block 1), the bridge validates the data and transactions in that block and then replicates or transfers the information onto Blockchain B (e.g., as Block 1').

Figure 2. Blockchain bridge between two networks

The blockchain bridge acts as a mediator between the two networks, allowing assets and data to be transferred between them simultaneously. Network A transactions are transmitted to the blockchain bridge, which then transfers the assets or data to Network B. In contrast, transactions initiated on Network B are transmitted to the blockchain bridge, which then transfers the assets or data to Network A. The purpose of a blockchain bridge is to facilitate interoperability between different blockchain networks that may have different technical specifications, consensus mechanisms, or smart contract languages. A blockchain bridge is essentially a translator between various blockchain protocols, facilitating efficient asset transfers and communication. This is crucial because it allows users to access a wide range of decentralized applications and services that may be available on different blockchain networks. The Ethereum bridge, which allows currency transfers between the Ethereum network and other blockchain networks such as Binance Smart Chain, is one example of a blockchain bridge [16, 17]. Another example is the Polkadot bridge, which connects multiple blockchains in the Polkadot ecosystem, allowing for seamless interoperability between them [18]. Blockchain bridges are an important development in the blockchain space because they enable greater interoperability between different blockchain networks, which can facilitate decentralization, scalability, and innovation. In previous studies by some researchers [19–24], the implementation of blockchain bridges depends on different technologies, such as: Hash Locks, Sidechains, Atomic Swaps, Bridge Validators, Multi-Signature Transactions, Bridge token, etc.

Hash time-locked contracts (HTLCs) are smart contracts that can be utilized to create a secure, time-limited transaction between two parties on different blockchain networks. They work by releasing a certain amount of cryptocurrency on one blockchain and releasing it to another party once certain conditions are met. HTLCs can be used to create trustful cross-chain transactions between different blockchains. Sidechains are a type of blockchain that is connected to the main blockchain but operates independently. They can be used to create a bridge between different blockchain networks by allowing tokens to be transferred between them. Sidechains can be used to create more scalable and flexible blockchain networks, as they can offload certain types of transactions to a separate network. Atomic swaps are a form of decentralized exchange that allows users to trade different currencies without the need for a centralized intermediary. They utilize smart contracts to execute a trustless transaction between two parties on different blockchain networks. Atomic swaps can be used to create cross-chain transactions between different blockchains without the need for a centralized exchange. Bridge validators are responsible for validating and verifying the transactions that occur between multiple blockchain networks. They ensure the accuracy and integrity of the bridge's operations. Multi-Signature Transactions require multiple parties to provide their signatures before executing a transaction. It enhances security and reduces the risk of fraud. Bridge tokens are a type of cryptocurrency that is used to facilitate cross-chain transactions between different blockchain networks. They create an attached version of a cryptocurrency on a different blockchain network, which can then be traded for the original currency. Bridge tokens can be utilized to create a bridge between multiple blockchain networks and enable greater interoperability between them.

In general, the technology that operates blockchain bridges is complex and diverse. It depends on the use of various technologies, such as smart contracts, sidechains, and atomic swaps, to establish a seamless and secure connection between multiple blockchain networks. These technologies work together to facilitate the transfer of assets and data across different blockchains. Atomic swaps are an important technology utilized in blockchain bridges. They enable the direct exchange of assets between different blockchain networks without the need for intermediaries. Atomic swaps require cryptographic protocols to ensure that the exchange is secure. This technological advancement facilitates the exchange of assets across blockchain networks without requiring the intermediation of centralized exchanges or external third-party intermediaries. Figure 3 is an illustration of a transfer mechanism that demonstrates the development of protocols and algorithms that are essential for executing Atomic Swaps. It illustrates the Ethereum and Bitcoin blockchain exchanges. This provides a comprehensive overview of the technical steps required to enable interoperability between various blockchain networks.

```python
from flask import Flask, jsonify, request

app = Flask(__name__)

@app.route('/transfer', methods=['POST'])
def transfer():
    # Get the transfer data from the POST request
    data = request.get_json()

    # Check and verify the data required for the transfer
    if 'votes' not in data or 'source_network'  not in data or 'destination_network' not in data:
        return jsonify({'error': 'Required data missing'}), 400

    votes = data['votes']
    source_network = data['source_network']
    destination_network = data['destination_network']

    # Return a JSON response with the transfer status
    return jsonify({'status': 'Transfer completed successfully'}), 200

if __name__ == '__main__':
    app.run()
```

Figure 3. Python API calls

The code presented in Figure 3 focuses on receiving and validating the necessary data for a transfer operation, assessing the presence of required fields such as 'votes,' 'source_network,' and 'destination_network.' Upon successful verification, it generates a JSON response confirming the completion of the transfer process. Blockchain interoperability encompasses the overarching objective of facilitating communication among various blockchains, requiring the development and adoption of shared standards and protocols [25]. In contrast, a blockchain bridge is a more specific technique designed to act as a conduit exclusively for data exchange between two or more distinct blockchain networks [26].

3. Related Works

Several research projects have been conducted in the field of blockchain technology to address the general issue of ensuring interoperability between various blockchain networks. It is essential to understand that allowing token transfers between various blockchains is a specialized endeavor and is not related to the issue of blockchain interoperability. Although token transfers are a key component of blockchain interoperability, the topic encompasses a wide range of technical issues and solutions that are intended to facilitate smooth communication and collaboration between various blockchain platforms. The main objective of general interoperability in the context of blockchain is to enable the decentralized and reliable transmission of arbitrary information between different blockchains through generic communication. According to Schulte et al. [27], the focus of blockchain interoperability is to enable various blockchains to connect generically, making it possible for them to transmit any data in a decentralized and trustless environment. The need for enhanced interoperability between blockchain systems is becoming increasingly evident, as efficient data transfer from one blockchain to another is critical for optimal interoperability within the blockchain ecosystem. To address this issue, Jin et al. [28] propose a roadmap and an architectural approach to enhancing chain collaboration. While using blockchain bridges can provide a variety of advantages, such as improved functionality and connectivity, it is essential to recognize the limitations and challenges that come with them. Below are some of the obstacles and difficulties associated with using blockchain bridges, including security risks, interoperability issues, concerns regarding centralization, scalability limitations, and regulatory issues. The scientific literature now has a variety of surveys and thorough literature studies that explore the obstacles and difficulties related to the topic at hand. It has been pointed out in various previous studies [29–35] that examine and analyze different aspects of the recognized limitations and challenges.

- ***Security Risks:*** One of the most significant challenges associated with blockchain bridges is the potential security risks associated with them. The process of transferring data or assets between different blockchain networks creates the possibility of attacks or exploits that can compromise the integrity and security of the entire blockchain ecosystem.
- ***Interoperability:*** Blockchain bridges are often designed to facilitate interoperability between different blockchain networks; however, the technology is still in its early stages. Consequently, there may be compatibility issues between different blockchain networks, which can cause problems with data or asset transfers.

- ***Centralization Concerns:*** Some blockchain bridges may employ centralized intermediaries to facilitate transfers between different networks. This could lead to concerns over centralization, which is against the decentralized nature of blockchain technology.
- ***Scalability:*** Blockchain bridges can be limited in terms of scalability, as the transfer of data or assets between different blockchain networks can be time-consuming and resource-intensive. This can reduce the overall efficiency of the blockchain ecosystem.
- ***Regulatory Challenges:*** The use of blockchain bridges can also pose regulatory challenges, as different blockchain networks may be subject to different regulatory frameworks. This can lead to legal and compliance issues that need to be addressed before widespread adoption of blockchain bridges.

To address these issues, researchers and developers are actively exploring new solutions and technologies. The field of blockchain bridges is experiencing considerable progress, such as Layer 2 solutions that process transactions off-chain and settle them on the main blockchain [36, 37]. There are also cross-chain DeFi protocols in development that enable cross-chain asset trading and liquidity provision [7, 38]. In addition, regulatory sandboxes are being established in some countries to provide a controlled testing environment for developing new blockchain technologies, such as blockchain bridges. Implementing inter-chain or cross-chain communication protocols poses a significant challenge due to the diverse designs and operational characteristics of individual blockchains, presenting a substantial barrier to establishing effective inter-chain communication [39]. It is difficult to integrate cross-chain communication protocols, given the complex differences in design and operational functionality across individual blockchains. However, despite the advantages of blockchain networks, there are still several challenges and limitations that require attention. Nonetheless, there have been real-world implementations of blockchain bridges. Several examples of blockchain bridge implementation are included below, providing real-world examples of how interoperability across multiple blockchain networks can be applied practically and achieved [40, 41]. These examples demonstrate how assets, data, and functionality may be connected to and moved efficiently between different blockchain ecosystems, creating a favorable environment for decentralized applications and opening cross-chain interactions.

- ***Polygon Bridge:*** Polygon is a Layer 2 scaling tool for Ethereum, which allows for faster and cheaper transactions. The Polygon Bridge is a bi-directional bridge that connects the Polygon network with Ethereum. The bridge allows for a seamless movement of assets between the two networks and has been beneficial in reducing congestion on the Ethereum network. The Polygon Bridge has been instrumental in enabling DeFi protocols such as Aave and SushiSwap to migrate to the Polygon network, which has resulted in lower transaction fees and faster confirmation times.
- ***Polkadot Bridge:*** Polkadot is a multi-chain network that allows for interoperability between multiple blockchain networks. Polkadot Bridge connects Polkadot with other networks such as Ethereum and Bitcoin, allowing for the effortless transfer of assets between them. The Polkadot Bridge has been instrumental in creating a more connected blockchain ecosystem, where different networks can work together to create decentralized applications.
- ***Binance Smart Chain Bridge:*** Binance Smart Chain is a high-quality blockchain that is compatible with the Ethereum Virtual Machine. The Binance Smart Chain Bridge connects Binance Smart Chain to other networks such as Ethereum and the Bitcoin network, allowing for the seamless transfer of assets between them. Binance Smart Chain has become a popular alternative to Ethereum, with several DeFi protocols such as PancakeSwap and BakerySwap being constructed on the network.
- ***Avalanche Bridge:*** Avalanche is a high-performance blockchain that provides smart contracts and interoperability. The Avalanche Bridge connects Avalanche to other networks such as Ethereum, allowing for the seamless exchange of assets between them. The bridge has helped to increase liquidity on the Avalanche network and has made it easier for developers to create decentralized applications that can be utilized across multiple blockchain networks.

Two significant insights learned from the utilization of blockchain bridges revolve around the crucial roles of security and community engagement. The vulnerability of bridges to potential attacks underscores the need to implement robust security measures to ensure the protection of transferred assets. Furthermore, the success of blockchain bridges heavily relies on the promotion of collaboration and garnering support from diverse blockchain communities, emphasizing the essential role of community involvement in achieving whole-system interoperability and advancing the overall effectiveness of such bridges. It is also important to have open communication channels to address any issues that may arise during the implementation of the bridge. In addition, the implementation of blockchain bridges has highlighted the need for interoperability between blockchain networks. The ability to transfer assets between different networks is crucial for the development of the blockchain ecosystem, and blockchain bridges have been instrumental in enabling this to occur. In blockchain bridge technology, several potential advancements have been identified, each with potential implications for industries and society. Furthermore, they have the potential to revolutionize various sectors, including finance, supply chain management, healthcare, and governance, by facilitating transparent and efficient processes, reducing intermediaries, and fostering trust and transparency. These advancements demonstrate innovative initiatives that aim to enhance interoperability, scalability, and security in blockchain networks.

- ***Increased Interoperability:*** Blockchain bridge technology will continue to improve interoperability between different blockchain networks, allowing for seamless movement of assets and data. This will enable more efficient and cost-effective transactions and could lead to increased adoption of blockchain technology across multiple industries.
- ***Expansion of Decentralized Finance:*** Decentralized finance (DeFi) has been one of the most popular use cases for blockchain technology, and blockchain bridge technology will play a crucial role in the expansion of DeFi. As blockchain bridges become more advanced, they will enable greater liquidity across different networks, which will enable more complex financial products and services to be developed.
- ***Cross-Chain NFTs:*** Non-fungible tokens (NFTs) have become more popular in recent years, with millions of dollars being spent on digital art and collectibles. As blockchain bridge technology progresses, it will be possible to create cross-chain NFTs, which can be traded on different blockchain networks. This will enhance the liquidity of NFTs and could lead to the creation of new markets for digital assets.
- ***Increased Security:*** Blockchain bridge technology will continue to improve security measures to safeguard assets being transferred across different networks. This will assist in preventing hacking and other security breaches that can result in loss of assets.
- ***Improved Supply Chain Management:*** Blockchain technology has already been used to improve supply chain management, and blockchain bridge technology will enable it to create a more comprehensive and transparent supply chain network. This will enable companies to monitor products and goods across multiple blockchain networks, increasing efficiency and reducing costs.

As blockchain technology continues to evolve, it is anticipated to bring about significant changes in various industries and government sectors. For businesses, blockchain technology has the potential to transform the way transactions are conducted, making them faster, secure, and cost-effective. Additionally, it provides transparency and immutability, which can lead to greater trust between businesses and their customers. Furthermore, blockchain technology can increase the efficiency and effectiveness of government services. It is becoming increasingly important for businesses and governments to embrace this technology to remain competitive and provide better service to their customers and citizens.

4. Blockchain Bridge on e-Voting

Blockchain bridges are essential in the development of decentralized services by facilitating the seamless transfer of digital assets across different blockchains. Such digital assets may include cryptocurrencies, tokens, and data records, among other items. Bridges provide interoperability between several blockchain networks, which could improve functionality. These bridges' introduction of fundamental interoperability has enormous potential to enhance the security and scalability of the larger blockchain ecosystem, as well as to enhance its effectiveness. The concept of the blockchain bridge, as illustrated in Figure 4, is an innovative approach, specifically in the field of electronic voting.

Figure 4. Blockchain bridge on e-voting

This approach, specifically designed for electronic voting systems, is evidence of the transformative potential of blockchain technology in transforming the dynamics of secure and transparent electoral processes. Its novel architecture not only showcases an innovative paradigm but also signifies a departure from traditional voting methodologies, presenting an avant-garde solution to the perennial challenges of fraud, pressure, and manipulation encountered in conventional voting systems. This methodology provides voters the opportunity to cast their votes on one blockchain network while ensuring the secure and transparent recording of these votes on a separate interconnected network. The use of blockchain bridges in such a manner can alleviate long-standing challenges encountered within traditional voting systems, tackling issues such as fraud, coercion, and vote manipulation. Moreover, by utilizing the immutable and transparent nature of blockchain technology, blockchain bridges provide transformative opportunities across various sectors and industries, including finance, supply chain management, and healthcare. Therefore, it is essential for both businesses and governments to adapt and remain consistent with the evolving blockchain landscape to remain competitive and provide enhanced services to their stakeholders.

The integration of blockchain bridges facilitates the creation of decentralized applications capable of interacting seamlessly across multiple blockchain networks. This opens avenues for the creation of sophisticated services and tools using smart contracts, thereby extending the range of use cases and potential benefits. This increased flexibility and connectivity can enable the creation of innovative solutions that were previously impossible to achieve within a single blockchain network. Furthermore, the use of blockchain bridges can enhance the security and transparency of decentralized applications by enabling the transfer of assets between networks while maintaining the integrity of the underlying blockchain protocols. Blockchain bridges are complex systems that involve multiple components to enable the transfer of digital assets between different blockchain networks. These components include bridge nodes, relays, and smart contracts. Smart contracts are self-executing digital programs that can automatically execute and enforce agreements between individuals without the need for intermediaries. These contracts are stored on the blockchain and can be utilized and executed by anyone with the necessary permissions. In the context of blockchain bridges, smart contracts provide a crucial role in facilitating the secure transfer of assets between different blockchain networks. They are responsible for ensuring that the assets being transferred meet the necessary requirements and that the transaction is executed securely and transparently. Relayers are a crucial component of blockchain bridge technology by broadcasting transactions across different networks. They act as intermediaries between the sender and receiver, facilitating the transfer of digital assets.

Bridge nodes are responsible for verifying and validating the transactions that are being executed. They ensure that the transactions comply with the rules and regulations of the respective blockchain networks and confirm that the transfer of assets is valid. Additionally, blockchain bridges also require consensus mechanisms to ensure the accuracy and integrity of the transactions. Consensus mechanisms involve a network of nodes coming to a collective agreement on the validity of a transaction and can be achieved through various methods such as proof-of-work or proof-of-stake. The integration of these components allows for the seamless transfer of digital assets across different blockchain networks, enabling decentralized applications to interact with each other and provide more complex services to users. Blockchain bridges are a crucial component of the blockchain ecosystem, which allows for the seamless transfer of digital assets across different blockchain networks. These bridges come in various types and designs, which are tailored to serve specific purposes. Alternatively, some bridges are intended to facilitate the transfer of digital assets between two different cryptocurrency networks, while others are intended to connect different blockchain-based applications or services. Overall, blockchain bridges enhance interoperability between different blockchain networks, enabling them to operate collectively and benefit from each other's strengths and abilities. The ability to work together across different blockchain networks can promote a more unified and integrated blockchain ecosystem, facilitating the development of innovative applications and services that were previously unachievable.

The study by Neziri et al. [1], as shown in Figure 5, illustrates a voting system that uses blockchain technology for electronic voting but involves more than one blockchain. This scheme incorporates various fundamental components, including a vote transfer mechanism coordinating seamless transitions between different blockchains. In this system, smart contracts and transmitters work together in a complementary manner to ensure the smooth and secure voting process. Most importantly, the transfer mechanism, also known as bridge nodes, is a crucial component of this architecture. These nodes perform essential functions, meticulously verifying transactions and ensuring compliance with the predefined rules and regulations imposed by the individual blockchain networks involved in the voting process. By employing cryptographic techniques, the system must effectively eliminate the voter's identity from their cast vote, ensuring strict privacy and confidentiality measures. This approach should be used to safeguard the sanctity of the electoral process by excluding any possible identification or tracking of individual votes, thus enhancing the overall legitimacy of the elections.

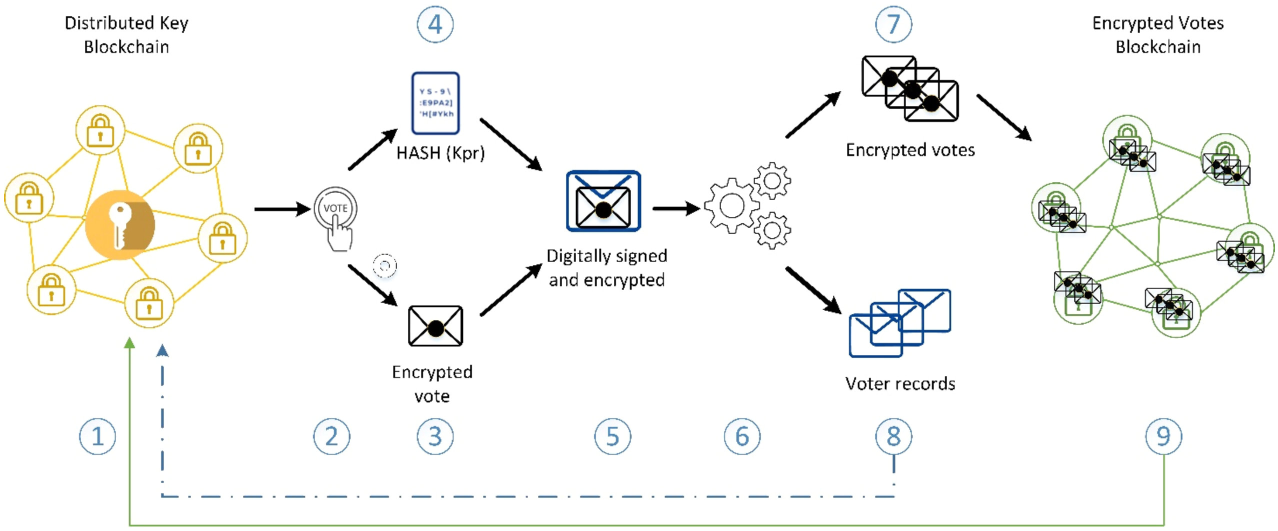

Figure 5. E-voting with multiple blockchains [1]

The mechanism, in step 6 of Figure 5, referred to as an anonymizer, serves the purpose of obfuscating the timestamps associated with votes, which are considered sensitive pieces of information that could potentially enable the identification of individual voters or their voting patterns. By utilizing a process of timestamp mixing, the anonymizer ensures that the temporal data associated with each vote is scrambled and shuffled in a manner that prevents easy linkage to individual voters. Furthermore, the anonymizer operates in conjunction with a larger data separation strategy that ensures voter data is kept separate from vote. This separation is crucial for safeguarding the privacy and security of voters, as it prevents any unauthorized or unintentional access to voter information that could undermine the integrity of the voting process. However, while timestamp mixing is an effective method for preventing voter privacy, it is not without its limitations. For example, it does not address the issue of vote integrity or prevent voting manipulation by malicious actors. To address these concerns, a more comprehensive approach is required, such as the use of a blockchain bridge.

A blockchain bridge is a technology that can help to secure the voting process by creating an immutable and tamper-proof record of all votes cast. By utilizing the power of blockchain, a decentralized ledger that is resistant to manipulation, a blockchain bridge can ensure that every vote is accurate and counted, without the risk of interference by third parties. It is essential to maintain voter anonymity within the system depicted in Figure 5 by implementing a specific methodology. Therefore, our proposed approach aims to substitute this mechanism with a blockchain bridge, as demonstrated in Step 6 of Figure 6. This approach enhances the system's security and transparency while safeguarding voter anonymity and safeguards the privacy of individual votes by using cryptographic techniques to separate voter identity from the vote cast. Such bridge access protects voter anonymity by maintaining personal identity separate from the voting process. This ensures that no vote can be traced, which enhances the legitimacy of the election. By effectively dissociating the voter's identity from their cast vote, the system eliminates any possibility of tracking individual votes, thereby enhancing the overall credibility and integrity of the electoral process.

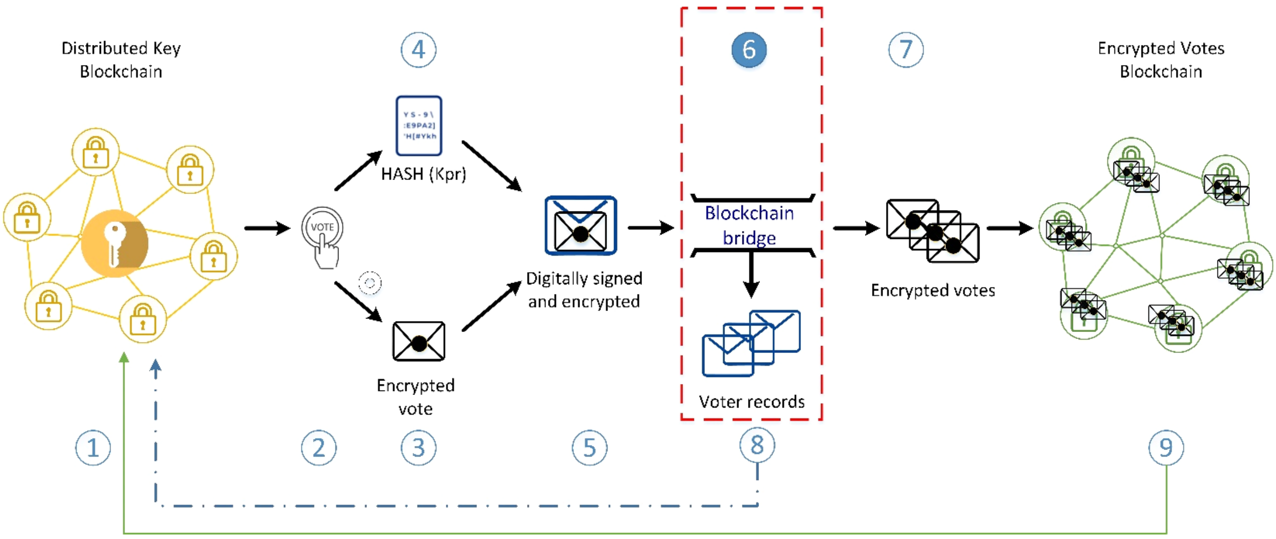

Figure 6. Replacing Anonymizer with Blockchain Bridge

By utilizing this approach, we can ensure that every vote is counted correctly and accurately, without compromising the privacy or security of individual voters. Replacing the traditional anonymizer mechanism with a blockchain bridge offers several benefits for enhancing the security of a voting system. Firstly, it guarantees the integrity of the voting process by creating an unalterable record of every vote cast. Secondly, it eliminates the need for trust in third-party intermediaries, such as centralized voting authorities. Finally, the system's design ensures voter privacy and anonymity by recording each vote in a manner that prevents the identification of individuals. In essence, substituting anonymizer mechanisms with blockchain bridges is a significant step towards achieving a more secure and transparent voting system. Blockchain technology allows us to establish an authentically decentralized and incorruptible voting process that ensures the integrity of each vote while simultaneously safeguarding the anonymity and privacy of individual voters.

5. Conclusion

Blockchain bridges are a relatively new concept in the world of blockchain and represent a nascent, but promising innovation within the realm of blockchain technology, aiming to facilitate seamless communication and interoperability among diverse blockchain networks. These bridges provide a viable solution to the enormous challenge of interoperability by fostering data exchange and connectivity among networks, thereby fostering a more cohesive and integrated ecosystem of blockchain-based technologies. Nonetheless, the underlying technology enabling blockchain bridges is complex and multifaceted, integrating smart contracts, decentralized nodes, cryptographic algorithms, and hash functions. These elements work synergistically to ensure secure and accurate transaction processing, thereby enabling interoperability across various blockchain networks.

While blockchain bridges are significant in addressing interoperability challenges and enabling asset transfers between distinct blockchain networks, critical constraints such as scalability and governance persist. The increasing number of users within these networks can potentially lead to longer transaction processing times and network congestion. Therefore, continuous research and development are essential to enhance blockchain networks' scalability and ensure their sustainable operation. Failure to address these issues may hinder the realization of the full potential inherent in blockchain networks.

In addition, blockchain bridges have emerged as promising solutions for enhancing interoperability and asset transfer among various blockchain networks, particularly in the context of electronic voting. Their fundamental strength lies in ensuring the complete detachment of voter identities from their respective votes, a crucial aspect of ensuring reliable and trustworthy elections. By establishing a robust separation between a voter's identity and their ballot, these bridges safeguard the integrity of the electoral process.

Continued exploration and refinement of blockchain bridge technology are essential for creating a more cohesive and integrated ecosystem of blockchain-based technologies. Through such endeavors, the untapped potential of blockchain technology can be utilized to achieve a more efficient and secure digital future.

In conclusion, the combination of blockchain interoperability and blockchain bridges underscores the essential pursuit of enabling seamless communication across multiple blockchain networks. While blockchain interoperability embodies a greater vision for achieving this interconnectedness, blockchain bridges serve as pragmatic tools to achieve this objective. These advancements collectively demonstrate substantial progress in enhancing the adaptability and efficacy of blockchain technology, promising transformative impacts across various applications, including cross-jurisdictional electronic voting.

6. Declarations

6.1. Author Contributions

Conceptualization, V.N. and B.R.; methodology, B.R. and V.N.; formal analysis, B.R., V.N., and R.D.; resources, V.N., B.R., and R.D.; writing—original draft preparation, V.N. and B.R.; visualization, V.N.; supervision, B.R.; project administration, B.R. and V.N.; funding acquisition, B.R., V.N., and R.D. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The research was funded by Project MESTI No. 2-814; however, the authors did not receive any financial support for the authorship or publication of this article.

6.4. Acknowledgements

The authors gratefully acknowledge the Ministry of Education, Science, Technology and Innovation, Kosovo for supporting this research.

6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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