Interoperability between blockchain platforms with cross-chain

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La tecnología *blockchain* requiere evaluar el estado actual de interoperabilidad entre sus plataformas con el fin de mejorar la eficiencia de las actividades que se lleven a cabo, y permitir la innovación y servicios nuevos. Se han propuesto soluciones para facilitar la interoperabilidad entre plataformas, entre las que se incluyen tecnologías *cross-chain*, las cuales pueden ser entendidas como un protocolo de comunicación. Algunas soluciones de interoperabilidad presentan problemas como, por ejemplo, estar limitadas al intercambio de activos, la ineficiencia en situaciones complejas e introducir un elemento de confianza centralizador que vaya en contra del principio de descentralización de las cadenas *blockchain*. La interoperabilidad depende de los estudios sobre consensos descentralizados; de la seguridad *cross-chain*; y de los mecanismos estandarizados que aseguren que las plataformas, independientemente de sus diferencias estructurales, puedan interactuar de manera segura, eficiente y escalable. Por consiguiente, se requiere un estudio sobre el estado de arte sobre *cross-chain*, que es la técnica más usada. Para ello, se siguieron las recomendaciones de Kitchenham y Charters (2007), y los criterios de calidad propuestos por Dybå y Dingsøyr (2008). Se realizaron búsquedas en el repositorio de Instituto de Ingenieros Eléctricos y Electrónicos (IEEE) y se identificaron 1.440 artículos. Luego de precisar la

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búsqueda y ejecutar el proceso metodológico, quedaron 14 artículos. Los resultados proporcionan un panorama del estado de arte sobre la interoperabilidad entre las plataformas *blockchain*, que indica que es un tema incipiente en el ecosistema *blockchain*.

Palabras clave: *blockchain*, *cross-chain*, interoperabilidad, plataformas *blockchain*

Interoperability between blockchain platforms with cross-chain

Blockchain technology requires evaluating the current state of interoperability between its platforms, to improve efficiency of the activities that are carried out and enable innovation and new services. Solutions have been proposed to facilitate interoperability between platforms, including Cross-chain technologies, which can be understood as a communication protocol. Some interoperability solutions present problems, e.g., being limited to the exchange of assets, inefficiency in complex scenarios, and introducing a centralizing element of trust that contradicts the principle of decentralization of blockchain networks. Interoperability depends on studies on decentralized consensus, Cross-chain security, and standardized mechanisms that ensure that platforms, regardless of their structural differences, can interact in a secure, efficient, and scalable manner. Therefore, a study on the state of the art related to Cross-chain, which is the most widely used technique, is necessary. So, the recommendations of Kitchenham and Charters (2007) and the quality criteria proposed by Dybå and Dingsøyr (2008) were followed. Searches were performed in the IEEE repository, identifying 1.440 articles. After refining the search and executing the methodological process, 14 articles remained. The results provide an overview of the state of the art on interoperability between blockchain platforms, indicating that this is an incipient topic in the blockchain ecosystem.

Keywords: blockchain, cross-chain, interoperbability, blockchain platforms

Interoperabilidade entre plataformas *blockchain* com *cross-chain*

A tecnologia *blockchain* requer a avaliação do estado atual da interoperabilidade entre as plataformas, a fim de melhorar a eficiência das atividades que se realizam e permitir a inovação e novos serviços. Têm sido propostas soluções para facilitar a interoperabilidade entre plataformas, incluindo tecnologias *cross-chain*, as quais podem ser entendidas como um protocolo de comunicação. Algumas soluções de interoperabilidade apresentam problemas como, por exemplo, estarem limitadas à troca de ativos, a ineficiência em situações complexas e introduzir um elemento centralizador de confiança que contraria o princípio de descentralização das cadeias *blockchain*. A interoperabilidade depende dos estudos sobre consenso descentralizado, segurança *cross-chain* e dos mecanismos padronizados que garantam que as plataformas, independentemente de suas diferenças estruturais, possam interagir de forma segura, eficiente e escalável. Portanto, é necessário um estudo sobre o estado da arte relacionado à *cross-chain*, que é a técnica mais utilizada. Para tanto, foram seguidas as recomendações de Kitchenham e Charters (2007) e os critérios de qualidade propostos por Dybå e Dingsøyr (2008). Buscas foram realizadas no repositório do Instituto de Engenheiros Elétricos e Eletrônicos (IEEE) e identificaram 1.440 artigos. Após focar a busca e a realizar o processo metodológico, ficaram 14 artigos. Os resultados fornecem uma visão geral do estado da arte em relação à interoperabilidade entre plataformas blockchain, indicando que se trata de um tópico emergente no ecossistema blockchain.

Palavras-chave: *blockchain*, *cross-chain*, interoperabilidade, plataformas *blockchain*

1. Introduction

Blockchain technology is a technology first proposed by Satoshi Nakamoto in 2008 (Darshan et al., 2023). Blockchain is a peer-to-peer (P2P) network that relies on complex cryptography to achieve immutability and anonymity in data storage and processing through distributed system architectures with consensus mechanisms. Blockchain systems allow users to reach consensus without the intervention of a third-party organization and solve the problems of trust and value of data on the Internet at a low cost. With its ability to store data and perform computations in a decentralized and immutable manner, blockchain technology shows potential in several application areas, such as cryptocurrencies, agriculture, healthcare, finance, energy, and supply chains.

Blockchain consists of a chronologically ordered chain of blocks that can record transactions between multiple peers in a decentralized P2P network, maintaining immutability and transparency. Data is stored using cryptographic codes (Zheng et al., 2019) and transactions are linked to cryptographic keys (Da Silva Rodrigues & Rocha, 2021). Blockchain platforms provide a decentralized solution for tracking and documenting transactions, creating globally distributed historical records of transactions that prevent counterfeiting and fraud (Mohurle & Patil, 2017).

Blockchain technology has attracted considerable attention due to its revolutionary potential in several areas. Since the emergence of bitcoin, the first practical example of blockchain, this technology has evolved significantly. Blockchain initially introduced the idea of a decentralized transaction system. Then, with the Ethereum blockchain, representing the blockchain 2.0 era, the capabilities of blockchain were expanded by introducing smart contracts, which allow the execution of autonomous and decentralized code. Currently, we are in the blockchain 3.0 era, where interoperability and communication between different blockchain platforms have become essential focus areas for the evolution of the blockchain (Harris, 2023).

Migrating to a new blockchain platform is becoming a necessity as more organizations continue to take note of this emerging technology and its vast capabilities (Lin et al., 2023). A growing challenge of blockchain technology will come down to how different blockchain networks can interact. This leads to a concept called interoperability, a characteristic of effective communication and direct exchange of information from one blockchain platform to another, while maintaining the essence of the individual blockchain, including irreversibility and traceability (Lin et al., 2023).

However, despite the progress, one of the main limitations and drawbacks of current blockchain platforms is the lack of interoperability between different networks. Independent blockchain networks are like isolated islands, facing significant challenges in data exchange and asset transfer, which results in fragmentation and inefficiency. Interoperability between blockchain platforms is crucial to enable a truly integrated blockchain ecosystem, where assets and data can flow freely between different platforms (Lin et al., 2023; Mao et al., 2023).

In this context, several solutions have been proposed to address the interoperability of blockchain networks, including cross-chain technologies. Cross-chain technologies, such as notary schemes, hash-locking, and relays, aim to facilitate communication between different blockchain platforms. Cross-chain technology can be understood as a chain-to-chain communication protocol. In the context of blockchain and cross-chain technology, a notary is an entity or a group of entities that act as trusted intermediaries in transactions between different blockchains. They verify, validate, and guarantee the transfer of assets or information between blockchains, replacing or complementing decentralized consensus mechanisms. Hash-locking uses hash-locking and time-locking technology to implement the function of currency exchange. Both parties need to lock the relevant tokens, the recipient will determine the receipt within the time limit and send the proof of receipt to the initiator, the initiator uses the proof of receipt to unlock and obtain the locked tokens from the recipient. Relays can send cross-chain transaction data to each node according to the underlying blockchain technology, making the entire transaction process clear and transparent. However, these technologies face specific challenges: notaries can be malicious, hash-locking limits application scenarios to asset exchange, and relays are difficult to implement in real scenarios. Furthermore, many protocols rely on centralized intermediaries, which contradicts the decentralization principle of blockchain prospect (Darshan et al., 2023; Harris, 2023; Zala et al., 2023).

Cross-chain is a technology that allows the transfer of information and values between different blockchains in a secure and efficient manner. This is crucial because each network operates independently, with its own rules and protocols, which often makes them incompatible with each other. In short, cross-chain is an essential advancement for the development of blockchain technology. By enabling communication between different networks, it creates an ecosystem that is more integrated, efficient and safe, opening doors to innovations that drive the growth of this technology.

Cross-chain technology can solve the 'data island' effects generated by a single chain, i.e. a set of isolated data, since this technology essentially has the function of sending data from one chain A to another chain B in a secure and reliable way, in addition to being able to consult, store and update information in B (Zala et al., 2023).

A systematic literature review (SLR) is presented with the objective of analyzing the state of the art on the use of cross-chain to facilitate interoperability between different blockchain platforms. Due to the growing evolution of blockchain technology and due to the various fields and use cases that can positively aggregate, an evaluation of the current state of interoperability between its platforms is necessary, to allow the improvement of activities that are already carried out on blockchain platforms and enabling innovation and use of new services.

Although there are several proposals and studies that address interoperability between blockchains, the literature still lacks a systematic analysis that organizes, compares, and critically evaluates these approaches in a comprehensive manner. Many works, for instance, propose specific solutions without discussing their scalability, practical feasibility, or compatibility with decentralization principles and the technologies used. Moreover, there is a lack of studies that classify these solutions based on criteria such as security, efficiency, degree of decentralization, use of frameworks, methodologies and technologies employed, and applicability. This systematic review aims to fill these gaps by identifying, analyzing, and categorizing the main cross-chain approaches, highlighting their benefits, limitations, and opportunities for future research. In doing so, this study seeks to contribute to the development of a more integrated and functional blockchain ecosystem.

This article is organized around this introduction. Section 2 describes the methodology used to develop the literature review. Section 3 presents the results and discussion where some questions are answered, and the analysis of the articles is discussed. Finally, section 4 presents the conclusion of this paper.

2. Methodology

A SLR was conducted to identify works that address interoperability between blockchain platforms, with an emphasis on cross-chain technology. The objectives were to provide elements for the presentation of research data, discover the most suitable system for data collection and analysis, and understand the available studies related to interoperability between blockchain platforms.

Initially, the first step of the methodology (Kitchenham & Charters, 2007) applied to carry out this literature review was the definition of the research questions. Thus, based on gaps identified in the literature, the following research questions were formulated:

1. Does the article discuss interoperability between blockchain platforms?

While numerous studies mention interoperability in blockchain systems, many only address the concept tangentially or without sufficient technical detail. Therefore, it is important to identify which work explicitly focuses on this topic, distinguishing between superficial mentions and in-depth proposals.

2. If there is a proposal for interoperability between blockchain platforms, how does this interoperability occur?

Several technological approaches have been proposed to enable interoperability, such as notary schemes, hash-locking, relays, and oracles (Gao et al., 2020; Sun et al., 2022). However, few studies systematically categorize or compare these methods. Understanding how interoperability is implemented is essential to evaluate the maturity and diversity of the current solutions.

3. What is the forecast for the evolution of interoperability between these platforms?

There is little consensus in the literature about the future direction of interoperability solutions. While some works suggest greater reliance on decentralized mechanisms, others indicate the growth of platform-specific or consortium-led models (Harris, 2023). Mapping these perspectives can help outline research trends.

4. What are the opportunities and challenges for interoperability between blockchain platforms?

Several studies identify technical, organizational, and regulatory barriers to interoperability, but often do so in isolated or fragmented ways (Darshan et al., 2023;

Harris, 2023; Zala et al., 2023). A consolidated view of the opportunities and challenges can guide researchers and developers toward more effective strategies.

Based on the research questions, keywords were subsequently defined: blockchain, interoperability, platforms, cross-chain. With the definition of the keywords, the search string was defined: *(blockchain) AND (interoperability OR compatibility) AND (blockchain platforms)*. Later, another search string was created, to perform another search for articles: *(blockchain) AND (interoperability OR compatibility) AND (cross-chain)*.

The search repository used was from IEEE https://ieeexplore.ieee.org/Xplore/home.jsp. This repository was chosen because IEEE is one of the most widely used repositories of scientific articles. From this initial stage, the inclusion and exclusion criteria were defined for the articles identified in the search with the search string in the IEEE repository:

- Inclusion criteria:

1) The paper discusses interoperability between blockchain platforms through cross-chain technology.
2) The paper presents an application, lessons learned, case study, or best practices.
3) The paper was published after 2015.
4) The paper is written in English.
5) If duplicate articles are identified in the search, the most recent one should be included.

- Exclusion criteria:

1) Studies prior to 2015
2) The focus of the study is not related to the research questions.
3) The language is not English.
4) The work is not available for download in full and free of charge.
5) The retrieved paper is repeated.

In addition to the inclusion and exclusion criteria, it is considered critical to evaluate the quality of studies. Based on the work issued by Keele University (Dybå & Dingsøyr, 2008; Keele, 2007), the following quality questions were used in the selection process, with only studies for which the answers were satisfactory being kept in the systematic review.

- (QQ1) Is the solution clearly detailed?
- (QQ2) Aren't the proposed technologies obsolete?
- (QQ3) Are the results and conclusions clearly explained?
- (QQ4) Is there a clear description of the proposed solution environment?
- (QQ5) Are the objectives and motivation of the research clearly defined?
- (QQ6) Does the study address interoperability between blockchain platforms?
- (CQ7) Is the methodology adequate to answer the research question?

2.1. Execution

The initial search was carried out using two predefined search strings across selected digital databases. The first search string returned a total of 1440 articles, encompassing a broader scope related to blockchain and interoperability. The second, more refined string was applied to narrow the scope specifically to cross-chain interoperability. After removing duplicates in both searches and excluding by reading the titles and abstracts of the set of articles retrieved with the first string, the merged set contained 128 unique records. The first screening phase involved analyzing the titles and keywords of the 128 records to assess their alignment with the research objectives. Articles that clearly did not focus on blockchain interoperability or cross-chain technologies were excluded based on predefined inclusion and exclusion criteria. In this stage, the abstracts of the remaining articles were carefully read to determine the centrality of cross-chain solutions in each work. After applying the criteria again, the sample was reduced to 49 articles.

The final step involved a full-text reading of the 49 articles to verify thematic relevance, methodological rigor, and availability of complete content. After this rigorous assessment, 14 articles were selected for final analysis. That analysis was made on the articles by reading the articles selected in the previous step in full, to have another filter that was even more restrictive than what would be selected, deciding to focus on the articles that addressed cross-chain. So, after applying all the quality criteria, excluding duplicate articles and those that could not be downloaded in full, 14 articles remained.

3. Results

To analyze the 14 selected articles, questions were formulated based on abstract reading of the previous selection phase, we sought to identify what the work proposes to solve, what solution is presented and what benefits, gaps and main characteristics of the proposal are. The following questions were developed for this analysis:

1) Is the article based on a permissioned blockchain?
2) Does the article discuss interoperability between blockchain platforms and/or systems?
3) Does the article propose any application programming interface (API) or make use of an existing one?
4) Is any blockchain-based architecture proposed?
5) Is any framework used or proposed?
6) Is any methodology used or proposed for the implementation of blockchain in the context of the article?
7) Does the article use smart contracts for interoperability of blockchain platforms?
8) Does the article use or propose a consensus protocol for interoperability?
9) What benefits are presented in the article?
10) What are the article's shortcomings or gaps?

Based on the identification of the answers to these questions, which are shown in detail in the appendix, the current research context was analyzed as discussed below.

3.1. Articles analysis

Based on the responses from the 14 articles, there is a diversity of approaches regarding the use of permissioned blockchains. Although some articles clearly explore the application of permissioned blockchains, such as articles from Darshan et al. (2023), Gao et al. (2020), Sun et al. (2022), and Yang et al. (2021), most of the articles focus on technologies associated with public blockchains or do not provide enough details to clearly determine the type of blockchain, such as articles from Ke et al. (2022), Lin at al. (2023), Westerkamp and Küpper (2022), and Zala et al. (2023). On the other hand, articles from Harris (2023), Li et al. (2022), Monika et al. (2021), and Sigwart et al. (2021) highlight the use of public and decentralized blockchains, such as Ethereum and Bitcoin, or mention public testnets such as Ropsten, Kovan and Goerli (Monika et al., 2021).

The mention of the use or proposal of APIs is present in a small portion of them, with few articles describing the use of specific APIs for interaction with blockchain platforms. However, most articles do not provide explicit information on the use of APIs. Articles from Härer (2022), Monika et al. (2021), and Zala et al. (2023) clearly mention the use of existing APIs to facilitate interaction with blockchain platforms. On the other hand, most articles do not specifically mention APIs or their application within the scope discussed. Articles such as the ones from Darshan et al. (2023), Li et al. (2022), Lin at al. (2023), Mao et al. (2023), Sun et al. (2022), and Westerkamp and Küpper (2022) suggest, although direct mention of APIs is not present, given the context of interoperability or related technologies, and given the technologies that are present in the article and in the studies, it is possible that APIs are being used. However, articles such as the ones from Gao et al. (2020), Harris (2023), Ke et al. (2022), Sigwart et al. (2021), and Yang et al. (2021) do not explicitly mention the use of APIs, which may indicate that the main focus is on other aspects of blockchain technology or that this information was not considered relevant to the objectives of the work.

The analysis of the responses to the 14 articles reveals that the majority propose or discuss different blockchain-based architectures, with a strong focus on interoperability and communication solutions between various blockchain networks. These architectures vary significantly in terms of complexity, consensus mechanisms, and supporting technologies, reflecting the diversity of approaches in this domain.

The use of frameworks is not mentioned in most articles, with only a few explicitly mentioning specific tools to support the development or implementation of the proposed solutions. The articles from Härer (2022), Monika et al. (2021), Sun et al. (2022), and Zala et al. (2023) mention the use of frameworks, while most of the other articles do not make any explicit reference.

The analysis of the responses about the methodology used or proposed for the implementation of blockchain in the 14 articles reveals a variety of approaches, focusing on experimentation, theoretical analysis, practical implementation, and mechanisms of validation to ensure interoperability and security in the proposed solutions.

Based on the responses from the 14 articles, most of them mention the use of smart contracts to facilitate interoperability between blockchain platforms, while some do not explicitly reference this feature. Articles that clearly mention the use of smart contracts include articles from Harris (2023), Li et al. (2022), Lin et al. (2023), Mao et al. (2023), Westerkamp and Küpper (2022), and Zala et al. (2023). These articles point to the use of smart contracts as an important part of interoperability solutions between blockchain platforms, employing this technology to manage transfers, interchain communication, and state synchronization. Sun et al. (2022) use smart contracts on both Hyperledger Fabric and Ethereum to manage cross-chain transactions and liquidation penalties, highlighting the applicability of smart contracts on both permissioned and public platforms. Monika et al. (2021) mention the use of swap contracts to manage interoperability between Ethereum networks, allowing atomic exchanges of assets between different blockchain networks. Gao et al. (2020) present the use of smart contracts on the source and target blockchains to interact with off-chain oracles and facilitate data transfer, a common approach to ensuring data integration between different systems. Sigwart et al. (2021) use smart contracts to manage the transfer of assets between blockchains, ensuring that assets on one chain can be claimed on another. Ke et al. (2022) implement hash time locked contracts (HTLCs) and cross-chain communication (CCC) as interoperability mechanisms, which are smart contracts designed to facilitate secure and atomic transactions between different blockchains. Papers from Darshan et al. (2023), Härer (2022), and Yang et al. (2021) do not explicitly mention the use of smart contracts for interoperability.

Regarding the use of consensus protocols for interoperability, some works address this issue, although the approach and focus vary between them. Papers from Gao et al. (2020), Lin at al. (2023), Mao et al. (2023), and Zala et al. (2023) explicitly mention the use of consensus protocols in the context of interoperability. Sun et al. (2022), although do not mention a specific consensus protocol, describe the use of a reputation and margin system for the selection and operation of notaries, which can be seen as a consensus mechanism to choose participants in cross-chain transactions. Yang et al. (2021) propose the use of Delegated Proof of Stake (DPoS) as the consensus protocol in the relay chain, ensuring interoperability between different blockchains. Papers from Darshan et al. (2023), Härer (2022), Harris (2022), Ke et al. (2022), Monika et al. (2021), Sigwart et al. (2021), and Westerkamp and Küpper (2022) do not explicitly mention the use of a consensus protocol aimed at interoperability. In some cases, the solutions rely on the consensus algorithms already existing in each blockchain, such as proof-of-work (PoW) or proof-of-stake (PoS).

The main benefits highlighted in the 14 articles are:

- **Interoperability and data exchange**: Most articles (Darshan et al., 2023; Gao et al., 2020; Ke et al., 2022; Li et al., 2022; Lin et al., 2023; Mao et al., 2023; Monika et al., 2021; Sigwart et al., 2021; Yang et al., 2021) mention the ability to perform data and asset exchange between different blockchain networks as one of the main benefits. This enables fluid communication between decentralized systems, increasing collaboration and information sharing.

- **Accessibility and efficiency**: Greater efficiency and cost reduction are highlighted in several articles (Harris, 2023; Lin et al., 2023; Mao et al., 2023; Monika et al., 2021; Zala et al., 2023), especially regarding transaction automation and the elimination of intermediaries, facilitating the transfer of assets quickly and reliably.

- **Security**: Security is an important benefit highlighted in several papers (Darshan et al., 2023; Gao et al., 2020; Ke et al., 2022; Sigwart et al., 2021; Sun et al., 2022; Yang et al., 2021; Zala et al., 2023). Security is ensured using technologies such as asymmetric cryptography (Gao et al., 2020), inclusion proofs (Sigwart et al., 2021), smart contracts (Monika et al., 2021), and hash-locking (Sun et al., 2022), which protect against common attacks and ensure data integrity.

- **Decentralization**: Decentralization is seen as a major benefit, especially in Sigwart et al. (2021), and Zala et al. (2023), allowing assets to be transferred between blockchain platforms without the need to trust centralized intermediaries. It also makes it possible for any user to complete transactions independently (Sigwart et al., 2021).

- **Scalability and innovation**: Some articles (Lin at al., 2023; Mao et al., 2023; Zala et al., 2023) mention that interoperability facilitates the scalability of blockchain platforms and enables the creation of new use cases and innovations in the blockchain ecosystem, opening doors for more complex and collaborative applications between platforms.

- **Flexibility**: Other articles (Gao et al., 2020; Härer, 2022; Monika et al., 2021; Westerkamp & Küpper, 2022) highlight the flexibility provided by these solutions, allowing platforms to adapt to different exchange scenarios and ensuring interoperability between heterogeneous blockchain systems (Gao et al., 2020; Yang et al., 2021).

- **Fault tolerance**: Increased fault tolerance is also a significant benefit, highlighted in the article of Sun et al. (2022), which compares this feature in relation to other projects and points out improvements in robustness against malicious nodes.

- **Transparency and standardization**: Some articles (Härer, 2022; Zala et al., 2023) mention transparency and standardization of queries as important benefits, allowing homogeneous access to data from different blockchains, which facilitates the integration of information.

Regarding the main weakness, the following are highlighted in the articles:

- **Scalability and complexity**: Several articles (Darshan et al., 2023; Gao at al., 2020; Harris, 2023; Lin et al., 2023; Mao et al., 2023; Sun et al., 2022; Yang et al., 2021; Zala et al., 2023) point out scalability and technical complexity issues as recurring shortcomings. Implementing interoperability solutions between different blockchains platforms can be technically complex, with multiple steps and the need for coordination between platforms (Sun et al., 2022). This increases maintenance and efficiency challenges (Yang et al., 2021).

- **Security**: Several papers (Gao et al., 2020; Harris, 2023; Lin et al., 2023; Mao et al., 2023; Monika et al., 2021; Sun et al., 2022) mention security vulnerabilities. There are concerns about attacks on notary systems (Sun et al., 2022), reliance on oracles (Gao at al., 2020), and sharing of private keys (Monika et al., 2021), which can introduce critical flaws. These points suggest the need for continuous improvement to ensure protection against exploits and hacks.

- **Third-party dependency**: Dependency on notaries (Sun et al., 2022) and oracles (Gao at al., 2020) is mentioned as a weak aspect, as the security and reliability of the system can be compromised if these intermediaries fail or are targeted by attacks.

- **Cost**: The costs associated with interoperability are a concern in some papers (Ke et al., 2022; Sigwart et al., 2021). The high gas consumption[1] in cross-chain transactions on Ethereum, for example, can significantly increase the cost of transfers (Sigwart et al., 2021). This represents an obstacle to the widespread adoption and efficient use of these solutions.

- **Time and performance**: Some solutions are criticized for their high setup and transaction verification time (Yang et al., 2021). The dependence on the relay to collect information (Sigwart et al., 2021) and the short blocking time may be insufficient for real scenarios, impacting performance and usability (Monika et al., 2021).

- **Limited support and adaptations**: Some solutions have limitations in supporting advanced features and need for adaptations to existing blockchains (Härer, 2022; Sigwart et al., 2021). Limited support for complex queries and the need to modify systems to implement certain techniques are cited as barriers (Sigwart et al., 2021).

- **Liquidity and usability**: Problems of lower liquidity in blockchain exchanges and user experience challenges are also considered in (Harris, 2023). This may hinder the adoption of interoperability technologies.

1 Ethereum gas is a fee paid to process transactions and execute contracts on the Ethereum blockchain, i.e., it is the fee paid to use the Ethereum network, and is measured in gwei, which is short for gigawei. One gwei is equal to one billionth of an ether (ETH).

3.2. Discussion

Interoperability between blockchain platforms reveals a scenario in which, despite significant advances, many challenges persist, opening opportunities for new research and technological solutions. One of the main obstacles to interoperability between blockchain platforms is the intrinsically isolated nature of these networks. This is because each blockchain has its own rules, consensus algorithms, and architectures, which in turn make direct communication and the sharing of data and assets difficult. Technologies such as hash-locking, notary schemes, and relays have been proposed to address this limitation, but they all face practical difficulties. Hash-locking, for example, is limited to the exchange of assets and is not effective in more complex scenarios, such as smart contracts inter blockchain. Notary schemes, on the other hand, introduce a centralized element of trust, which goes against the principle of decentralization that defines blockchain networks. Relays, on the other hand, offer interconnection potential, but are complex to implement and still present scalability and efficiency challenges (Darshan et al., 2023; Harris., 2023; Zala et al., 2023).

Furthermore, another critical aspect is security. Protocols that connect different blockchains, such as cross-chain bridges, can be vulnerable to attacks, which in turn end up compromising the trust and security of transactions. In this same logic, issues such as double spending and relay attacks still represent a considerable risk. Likewise, the decentralization of interoperability solutions is also a major challenge, as many proposals still depend on centralized intermediaries, which can create single points of failure and compromise the security and efficiency of the system (Härer, 2022; Mao et al., 2023).

This reflects the interoperability paradox: achieving communication across chains often requires reintroducing centralized elements or compromising performance, which undermines the foundational values of blockchain. In other words, the more interoperable a system becomes, the more it risks deviating from decentralization and trustlessness — two core principles of blockchain design.

However, despite these challenges, there are promising opportunities in the field of interoperability. Emerging technologies such as sidechains[2] and interoperability projects such as Polkadot and Cosmos have advanced in the search for decentralized solutions that can connect blockchain platforms efficiently. These platforms offer flexible

2 Sidechain is a scheme to interoperate, extend or upgrade two blockchain platforms. Usually one blockchain (sidechain) anchors another target blockchain (main chain), and the sidechain is connected to the main chain as an independent system through an inter-chain protocol.

frameworks so that different blockchains can share data and assets in a secure and scalable manner, using mechanisms such as PoS and cross-chain validation (Härer, 2022; Harris, 2023; Mao et al., 2023; Sigwart et al., 2021; Zala et al., 2023).

The use of smart contracts for communication between blockchain platforms also presents a growing opportunity. By implementing smart contracts that guarantee the integrity of transactions between different networks, without the need for intermediaries, it becomes possible to perform more complex operations, such as the execution of these contracts between heterogeneous platforms (Gao et al., 2020; Harris, 2023; Ke et al., 2022; Li et al., 2022; Mao et al., 2023; Monika et al., 2021; Sigwart et al., 2021; Westerkamp & Küpper, 2022; Zala et al. 2023).

Currently, solutions such as Polkadot and Cosmos are developing interoperability solutions, enabling efficient cross-chain transactions through hubs and parachains[3]. These projects promise to improve the security and scalability of interactions between blockchain platforms, while reducing technical barriers. In addition, the Interledger Protocol (ILP)[4], focused on interoperability between different ledgers, aims to integrate blockchain networks securely, without the need for a centralized blockchain (Harris, 2023; Sun et al., 2022; Zala et al., 2023).

However, despite these advances, there is still much room for progress, especially in terms of scalability, security, and the creation of standardized protocols that can be applied to multiple blockchain networks. Therefore, future research should focus on improving cross-chain consensus mechanisms, reduction of security vulnerabilities and in creation of more decentralized and efficient solutions for interoperability.

Overall, the blockchain interoperability landscape remains diverse and fragmented. While there is clear progress in developing technical solutions, there is a lack of consensus on the innovative and governance models that should guide these implementations. This reinforces the need for future work, not only proposing new protocols, but also developing theoretical frameworks that can unify the understanding between different approaches and provide a more comprehensive and simplified vision for cross-chain interoperability.

3 Parachains refer to blockchain networks that can be adapted to varying degrees for certain applications and purposes.

4 The main purpose of ILP is to support all distributed ledgers (blockchain), the transaction between ledgers and value transfers. ILP is not a ledger, and no consensus procedure is required. It offers a top-notch cryptographic custody system that allows the transfer of funds and currencies between accounts.

4. Conclusions

Interoperability between blockchain platforms continues to be a field of great relevance for the future of decentralized technologies. Through this literature review, it was possible to identify both the advances and the barriers that still need to be overcome so that interoperability solutions, such as cross-chain, become fully functional, scalable and reach their maximum potential.

Although technologies such as hash-locking, notary schemes, and relays have been developed to facilitate communication between blockchain networks, they face practical challenges, such as limitations on the exchange of assets and centralization in some mechanisms, which goes against the fundamental principle of decentralization.

Newer solutions, such as Polkadot and Cosmos, which use sidechains and parachains, have shown great potential by offering greater scalability and security in interactions between blockchains. At the same time, the use of smart contracts is emerging as an effective way to facilitate more complex transactions and operations between networks, reducing the need for intermediaries and promoting a more decentralized ecosystem (Sun et al., 2022; Zala et al., 2023).

However, progress so far still points to the need for further research and innovation. Key challenges such as security, scalability, and protocol standardization still need to be comprehensively addressed. The adoption of cross-chain solutions on a large scale will depend on the ability of researchers and developers to overcome these limitations and create platforms that can operate efficiently and reliably across different blockchain networks.

Therefore, the future of interoperability between blockchain platforms is promising, but it depends on further advances in areas such as decentralized consensus, cross-chain security, and standardized mechanisms that can ensure that blockchain platforms, regardless of their structural differences, can interact in a secure, efficient, and scalable manner.

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Authors declare that, throughout the research process, there has not been any sort of personal, professional, or economic interest that may have influenced the researchers' judgement and/or actions during the elaboration and publication of this article.

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Appendix
Detailed identification of responses

1. *Towards a novel interoperability management scheme for cross blockchain transactions* (Yang et al., 2021)

Is the article based on a permissioned blockchain?

Yes, the article mentions the use of private (permissioned) blockchains to implement the proposed scheme.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the paper proposes an interoperability management scheme for transactions between different blockchains, ensuring compatibility between heterogeneous blockchains.

Does the article propose any API or make use of an existing one?

The article does not specifically mention the existence of an API.

Blockchain based architecture proposed?

The architecture involves two private/public blockchains linked by a relay chain based on the DPoS consensus protocol.

Is any framework used or proposed?

The article does not specifically mention a framework used.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology includes the creation of an interoperability scheme, involving several detailed steps, such as key generation, information exchange between members of different blockchains and signature verification to ensure the security and consistency of transactions.

Does the work use smart contracts for the interoperability of blockchain platforms?

The article does not mention the use of smart contracts for interoperability.

Does the work use or propose a consensus protocol for interoperability?

Yes, DPoS consensus protocol is used in the relay chain to ensure interoperability between different blockchain.

What benefits are presented in the article?

- Compatibility between heterogeneous blockchains.
- Guarantee of correctness and consistency of exchanged data.
- Improved security of cross blockchain transactions.

What deficiencies or gaps were found in the article?

The article does not explicitly discuss deficiencies, but possible deficiencies may include:

- Complexity in implementing and maintaining the scheme.
- Relatively long time to set up and verify transactions.

The main features proposed in the article are:

- The proposed scheme avoids the need for an intermediary institution, reducing management costs and transaction risks.
- Using DPoS in the relay chain allows compatibility between blockchains with different consensus protocols.
- The security of the scheme is based on the difficulty of the Elliptic Curve Discrete Logarithm Problem (ECDLP) (Yang et al., 2021).
- The study discussed the feasibility of the scheme through experiments, with specific times for different phases of the process.

2. *A decentralized cross-chain service protocol based on notary schemes and hash-locking* (Sun et al., 2022)

Is the article based on a permissioned blockchain?

Yes. The article mentions using Fabric as a blockchain, which is a permissioned blockchain platform.

Does the article discuss interoperability between blockchain platforms and/ or systems?

Yes. The proposed protocol is designed to enable the transfer of tokens between different blockchains, specifically between the Fabric Blockchain and the Ethereum blockchain.

Does the article propose any API or make use of an existing one?

Information about the existence of an API was not explicitly mentioned.

Is there any proposed architecture based on blockchain?

The protocol architecture includes a notary system, where there is a primary notary and a secondary notary that coordinate transactions across the blockchains. The primary notary is responsible for receiving the list of transactions and selecting the secondary notary. The secondary notary acts as a link for cross-chain transactions.

Is any framework used or proposed?

Yes, the article mentions the use of Hyperledger Fabric.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The process described in the article follows an experimental and practical approach, with the experiments being set up using two specific blockchains (Hyperledger Fabric and Ethereum). The implementation takes place in a cloud server environment, and the performance and fault tolerance analysis are performed through comparative experiments.

The methodology applied to evaluate the effectiveness of the protocol involves the following steps:

1) **Experimental setup**: Alibaba Cloud is used, with servers running Ubuntu 18.04, Hyperledger Fabric as blockchain A and Ethereum as blockchain B. Chaincode is implemented in Java for Fabric, and smart contracts are written in Solidity for Ethereum.
2) **Performance comparison**: The proposed protocol is compared with the *BitXHub* project, analyzing the time cost of transactions and the efficiency in electing notaries.
3) **Fault tolerance analysis**: The paper evaluates the impact of different percentages of malicious nodes on transaction success, showing how the protocol handles failure situations.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes. Smart contracts are used on both Fabric and Ethereum to manage cross-chain transactions and liquidation penalty management.

Does the work use or propose a consensus protocol for interoperability?

Information about a specific consensus protocol for interoperability was not explicitly mentioned in the paper. However, the selection and operation of notaries is based on a reputation and margin system, which can be seen as a form of consensus for the selection of participants in transactions.

What benefits are presented in the article?

- **Increased security**: Combining notaries and hash-locking, preventing common attacks
- **Incentives and penalties**: To ensure that participants act honestly
- **Efficiency**: Superior to the BitXHub (Sun et al., 2022) project in terms of transaction time
- **Fault tolerance**: Better than traditional notary schemes

What deficiencies or gaps were found in the article?

- **Dependence on notaries**: Despite the security mechanisms, there is still a significant dependence on notaries for the operation of the system.
- **Complexity**: Adding multiple steps and participants to the execution of transactions can add complexity to the process.

The following characteristics may be cited in the work:

- **Election of notaries based on reputation and margin**: This system encourages honest behavior and penalizes malicious behavior.
- **Penalty management**: Settlement penalties are used to deter dishonest behavior.
- **Practical interoperability**: The proposed architecture shows a practical and implementable solution for interoperability between different blockchains.
- **Resilience to attacks**: Mechanisms to prevent attacks such as sore loser and wormhole

3. *Cross-chain oracle-based data migration mechanism in heterogeneous blockchain* (Gao at al., 2020)

Is the article based on a permissioned blockchain?

Yes, both the source and destination blockchains are blockchain consortia, which are usually permissioned blockchains. These types of blockchains ensure the security and credibility of the nodes and the blockchain.

Does the article discuss interoperability between blockchain platforms and/ or systems?

Yes, the proposal of the article is to achieve interoperability between two heterogeneous blockchains, using a data migration oracle to facilitate this interaction.

Does the article propose any API or make use of an existing one?

There is no explicit mention of an API in the article.

Is there any proposed architecture based on blockchain?

Blockchain framework that involves a source blockchain, a destination blockchain, and a data migration oracle that acts as an intermediary for data transfer between the two blockchains.

Is any framework used or proposed?

No specific framework is mentioned for implementing the proposed architecture.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology includes three main phases: preparation, execution, and migration. In preparation, related requirements are predefined; in execution, blockchains work independently to produce validated data and validated nodes; in migration, asymmetric cryptography is used to ensure data integrity and confidentiality.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, smart contracts are deployed on both the source and target blockchains to interact with the off-chain oracle and facilitate data transfer.

Does the work use or propose a consensus protocol for interoperability?

Yes, architecture uses consensus algorithms such as Paxos on the source blockchain and Practical Byzantine Fault Tolerance (PBFT) on the target blockchain to ensure consistency and security during the data migration process.

What benefits are presented in the article?

- **Interoperability**: Allows communication between heterogeneous blockchains.
- **Security:** Use of asymmetric encryption to ensure data integrity and confidentiality.
- **Reliability**: Consensus algorithms like Paxos and PBFT ensure consistency and security.

- **Flexibility**: Data migration oracle facilitates interaction between different blockchain.

What deficiencies or gaps were found in the article?

- **Dependence on oracles**: The security of the system depends on the robustness of the oracle, which is a third-party service and can be targeted by attacks.
- **Complexity**: Implementing an interoperability architecture between heterogeneous blockchains can be complex and require careful coordination between different systems.

The main features proposed in the research are:

- **Asymmetric encryption**: Essential to ensure security during data migration.
- **Data migration oracle**: Acts as a trusted intermediary for transferring data between blockchains.
- **Consensus algorithms**: Paxos and PBFT are used to ensure consistency and integrity of data on the source and destination blockchains.
- **Secure data migration**: The use of asymmetric cryptography and smart contracts ensures that data is transferred securely and reliably between blockchains.

4. Cross-chain technologies: Challenges and opportunities for blockchain interoperability **(Harris, 2023)**

Is the article based on a permissioned blockchain?

No, the article mainly mentions public and decentralized blockchain related technologies and platforms, e.g. Ethereum, Bitcoin and others.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article highlights several technologies and approaches for interoperability between different blockchains and systems, including inter-blockchain bridges, DEXs, and protocols like atomic swaps.

Does the article propose any API or make use of an existing one?

There is no specific mention of the presence or absence of APIs in the work.

Is there any proposed architecture based on blockchain?

The architecture varies depending on the technology or platform discussed in the articles, ranging from centralized solutions to decentralized platforms based on smart contracts.

Is any framework used or proposed?

There is no specific mention of a specific framework in the article.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The proposed methodology to facilitate interoperability between different blockchains includes the use of technologies such as inter-blockchain bridges, atomic swaps, and DEXs, among others.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, the texts mention the use of smart contracts to facilitate interoperability between different blockchains.

Does the work use or propose a consensus protocol for interoperability?

There is no specific mention of a consensus protocol exclusively focused on interoperability in the paper.

What are the benefits presented in the article?

Benefits cited include increased accessibility, intermediary-free asset transfer, increased liquidity, and the ability to explore trading opportunities across multiple blockchain platforms.

What deficiencies or gaps were found in the article?

Shortcomings include security vulnerabilities such as hacks and exploits, limited scalability, complexity in implementing interoperability, lower liquidity in inter-blockchain exchanges, as well as challenges in user experience.

The article highlights the importance of security, user education, regular code audits, and the continuous evolution of technologies to address challenges and improve interoperability between different blockchains.

5. "A survey on cross-chain technology: Challenges, development, and prospect" (Mao et al., 2023)

Is the article based on a permissioned blockchain?

The article mainly addresses cross-chain technologies, which involve interoperability between different blockchains, but is not focused on permissioned blockchains.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article discusses various interoperability technologies between different blockchain and systems such as Cosmos, Polkadot, and Interledger.

Does the article propose any API or make use of an existing one?

The paper does not explicitly mention a specific API for interoperability between blockchains.

Is there any proposed architecture based on blockchain?

Cross-chain technology discussed. For example, architectures such as sidechains/relays, tight coupling, and technologies such as Simplified Payment Verification (SPV) are mentioned.

Is any framework used or proposed?

The article does not mention the use of a specific framework for interoperability between blockchains.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology adopted to address interoperability between blockchain mainly involves the study and analysis of various cross-chain technologies and projects, comparing their advantages, disadvantages and future trends.

Does the work use smart contracts for the interoperability of blockchain platforms?

Cross-chain technologies discussed in the article involve the use of smart contracts to facilitate interoperability between different blockchains.

Does the work use or propose a consensus protocol for interoperability?

The article mentions the use of consensus protocols such as RAFT and proof-of-authority (PoA) and Ripple Consensus Protocol

What benefits are presented in the article?

Blockchain interoperability includes the ability to exchange assets, information, and collaborate on applications across different blockchain platforms, which the authors say can increase efficiency, reduce costs, and promote innovation.

What deficiencies or gaps were found in the article?

Some of the shortcomings discussed include security challenges, limited scalability, implementation complexity, and third-party dependency on certain interoperability solutions.

The paper highlights some important features that include the rapid development of cross-chain technology, its potential to revolutionize the blockchain industry, and the continued need to overcome technical and security challenges to achieve widespread adoption and practical application.

6. "An architecture that enables cross-chain interoperability for next-gen blockchain systems" (Darshan et al., 2023)

Is the article based on a permissioned blockchain?

Yes, the paper describes an architecture that involves several independent blockchains connected by a "MainChain", suggesting a permissioned approach in which the entities involved need to be validated and certified on the network.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article discusses interoperability between different blockchains, both public and private, as well as the connection between blockchain and external systems for data exchange and automation.

Does the article propose any API or make use of an existing one?

The article does not explicitly mention the use of an API, but given the context of interoperability between systems and blockchain it is likely that some form of API or communication protocol will be used to facilitate integration.

Is there any proposed architecture based on blockchain?

The architecture described involves multiple independent blockchains connected by a "MainChain", which acts as a connection point between them. The architecture also includes mixed nodes, transaction blocks and consensus algorithms between the blockchains.

Is any framework used or proposed?

The article does not explicitly mention the use of a specific framework.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The paper does not explicitly detail a specific methodology but describes the implementation of an interoperability solution between blockchain and systems, including experimental analysis and technical details about the proposed architecture.

Does the work use smart contracts for the interoperability of blockchain platforms?

The article does not explicitly mention the presence or absence of smart contracts for interoperability.

Does the work use or propose a consensus protocol for interoperability?

The paper does not specify a specific consensus protocol for interoperability but mentions the implementation of consensus algorithms such as PoW and PoS on different blockchains.

What benefits are presented in the article?

The benefits described include the ability to exchange data and transactions between different blockchains and systems, process automation, data security and decentralization of operations.

What deficiencies or gaps were found in the article?

The paper does not specify the shortcomings of the proposed solution, but possible challenges may include issues of scalability, security, and complexity in implementing and maintaining an interoperability architecture between blockchain and diverse systems.

7. *A survey on cross-chain asset transfer schemes: Classification, challenges, and prospects* (Lin et al., 2023)

Is the article based on a permissioned blockchain?

There is no specific information provided in the text about whether the blockchain discussed in the article is permissioned or not.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article discusses interoperability between different blockchain platforms for asset transfer. Various schemes and technologies are discussed to facilitate this interoperability.

Does the article propose any API or make use of an existing one?

There is no specific mention of an API in the text provided. However, some technologies discussed, such as the Interledger Protocol, may involve APIs to facilitate communication between different blockchains.

Is there any proposed architecture based on blockchain?

Blockchain interoperability such as hash-locking, notary schemes, sidechains/relays, and hybrid technology.

Is any framework used or proposed?

There is no specific mention of a framework in the article.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology is not explicitly defined in the text. However, the paper follows a systematic review approach of different cross-chain asset transfer schemes, analyzing their classification, challenges, and representative implementations.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, the text mentions the use of smart contracts in some interoperability schemes, such as in the case of sidechains/relays.

Does the work use or propose a consensus protocol for interoperability?

Yes, several schemes discussed in the paper involve consensus protocols to facilitate interoperability between different blockchain.

What benefits are presented in the article?

Benefits include the ability to transfer assets between different blockchains, improving the scalability and efficiency of transactions, as well as enabling new use cases and applications in the blockchain ecosystem.

What deficiencies or gaps were found in the article?

The shortcomings cited include challenges related to security, privacy, technical complexity, and efficiency of cross-chain transactions.

Some important features cited in the paper include the need to address challenges such as security, scalability, and privacy in blockchain interoperability. Furthermore, the research highlights the diversity of schemes and technologies available to facilitate cross-chain asset transfer, showing ongoing progress and challenges in this rapidly evolving field.

8. "Unlocking blockchain interconnectivity: Smart contract-driven cross-chain communication" (Zala et al., 2023)

Is the article based on a permissioned blockchain?

Blockchain is not clearly defined in the article.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article discusses interoperability between different blockchains to facilitate communication and asset transfer.

Does the article propose any API or make use of an existing one?

Yes, the article mentions using an API to track transaction progress.

Is there any proposed architecture based on blockchain?

The proposed architecture involves communication between two blockchain based systems, allowing the transfer and verification of assets between them.

Is any framework used or proposed?

The article does not explicitly specify a specific framework but mentions using the Truffle framework to implement smart contracts.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

Blockchain communication model.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, the article mentions the use of smart contracts to facilitate interoperability between blockchains.

Does the work use or propose a consensus protocol for interoperability?

Yes, the article suggests using consensus protocols on the blockchains involved to validate interoperability transactions.

What benefits are presented in the article?

Benefits include greater transparency, efficiency and security in the exchange of information and assets between different blockchain systems without the need for intermediaries.

What deficiencies or gaps were found in the article?

The paper does not explicitly mention shortcomings, but possible challenges may include security issues, scalability, and implementation cost.

The research highlights the importance of interoperability between blockchains to facilitate communication and transfer of assets between different platforms. This could have a major impact on several industries, promoting greater transparency, efficiency and security in transactions. In addition, the research discusses the potential application of smart contracts and consensus protocols to enable interoperability between blockchains.

9. *POLYBRIDGE: A cross-chain bridge for heterogeneous blockchain* (Li et al., 2022)

Is the article based on a permissioned blockchain?

No, the article mainly discusses interoperability between public (i.e., permissionless) blockchains.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article describes interoperability between different blockchain and systems.

Does the article propose any API or make use of an existing one?

There is no specific mention of an API.

Is there any proposed architecture based on blockchain?

The architecture described is based on the Poly Bridge, which includes modules such as the Poly Bridge Application, chains A and B, the Poly Chain, Relayers, and specific smart contracts.

Is any framework used or proposed?

There is no specific mention of a framework.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology is based on the implementation of the Poly Bridge, which uses relays, smart contracts and block header verifications to facilitate interoperability between blockchains.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, the article mentions specific smart contracts to facilitate interoperability between blockchain.

Does the work use or propose a consensus protocol for interoperability?

There is no specific mention of a consensus protocol for interoperability.

What benefits are presented in the article?

Benefits include the ability to interoperate between different blockchains, supporting more than 200 types of cryptocurrencies on 18 heterogeneous blockchains, in an extensible way and without modifications to the participating blockchains.

What deficiencies or gaps were found in the article?

The article does not explicitly discuss the shortcomings of the proposed technology.

Some important features presented in the paper include the extensibility of the Poly Bridge to support new blockchains without modification, the ease of use for users through the web application, and the approach to ensuring consistency of assets between blockchains during the interoperation process.

10. *SmartSync: Cross-blockchain smart contract interaction and synchronization* (Westerkamp & Küpper, 2022)

Is the article based on a permissioned blockchain?

It was not explicitly mentioned whether the blockchain is permissioned. SmartSync is a concept for synchronizing smart contracts across multiple blockchain networks but does not specify the type of blockchain.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, SmartSync aims to facilitate interoperability between smart contracts hosted on different blockchains.

Does the article propose any API or make use of an existing one?

It was not explicitly mentioned whether there is an API associated with SmartSync.

Is there any proposed architecture based on blockchain?

The SmartSync architecture involves creating proxy smart contracts and using Merkle proofs to synchronize states between blockchains.

Is any framework used or proposed?

It was not explicitly mentioned whether SmartSync is implemented in any specific framework.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The SmartSync methodology involves the periodic synchronization of smart contract states and the verification of the consistency of these states through Merkle proofs.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, SmartSync proposes the use of smart contracts to facilitate interoperability between blockchains.

Does the work use or propose a consensus protocol for interoperability?

It was not explicitly mentioned whether SmartSync implements any specific consensus protocol for interoperability.

What benefits are presented in the article?

Benefits of SmartSync include the ability to access *smart* contract states across different blockchains in a verifiable manner and ease of use for applications that rely on up-to-date data across multiple networks.

What deficiencies or gaps were found in the article?

The shortcomings of SmartSync were not specifically addressed in the article.

Some important features highlighted include the ability to synchronize smart contract states across different blockchains in a verifiable manner, which can facilitate the development of applications that rely on cross-blockchain interoperability. Furthermore, the SmartSync approach allows smart contract states to be updated in a timely manner and without the need for trust in executive entities.

11. *Towards interoperability of open and permissionless blockchain: A cross-chain query language* (Härer, 2022)

Is the article based on a permissioned blockchain?

No, the paper discusses an approach to data access on various blockchains, including open and permissionless blockchains (OPB), which suggests that it is not specifically focused on permissioned blockchains.

Does the article discuss interoperability between blockchain platforms and/ or systems?

Yes, the paper addresses interoperability between different blockchains and systems through a query language and processing architecture. This paper introduces a cross-blockchain query language for cross-blockchain data access. Like Structered Query Language (SQL), the language abstracts the implementation based on a data model compatible with the largest OPB today. The paper contributes a cross-blockchain query language by specifying a common data model, a standardized syntax, and a processing architecture. To answer query statements written by users or applications, data is read from multiple blockchain nodes, integrated into the common data model, and processed according to the statements.

Does the article propose any API or make use of an existing one?

Blockchain nodes but does not propose a new API. It makes use of existing APIs to interact with blockchain platforms, such as the APIs of Bitcoin Core, geth (for Ethereum), Cardano node, and AvalancheGo. These APIs are used by the prototype developed in the paper to query and validate data from full blockchain nodes. The system queries blockchain data through platform-specific APIs. These API calls allow the system to retrieve data such as transactions, blocks, and accounts directly from local nodes of synchronized blockchains.

Is there any proposed architecture based on blockchain?

The architecture is based on a query language, a data model and a processing architecture to enable homogeneous access to data across multiple blockchains.

Is any framework used or proposed?

No use of framework is mentioned, but the prototype implementation was carried out with the Eclipse Modeling Framework and Xtext to establish a domain specific language (DSL).

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The paper describes the methodology as an approach to developing a query language, data model, and processing architecture to enable homogeneous access to data across multiple blockchains.

Does the work use smart contracts for the interoperability of blockchain platforms?

There is no mention of using smart contracts for interoperability.

Does the work use or propose a consensus protocol for interoperability?

A specific consensus protocol for interoperability between blockchains is not mentioned.

What benefits are presented in the article?

Benefits include homogeneous access to data across multiple blockchains, standardization of queries, support for multiple blockchains in individual queries, and local validation of blockchain data.

What deficiencies or gaps were found in the article?

Shortcomings include limited support for advanced OPB concepts such as calculating transaction fees involving additional utility tokens, and limited functionality in queries such as only allowing inner joins and equality comparisons.

An important feature addressed in the paper is the attempt to standardize data access across different blockchains, which can facilitate the development of applications and systems that rely on data distributed across multiple platforms. Furthermore, the research highlights the importance of an integrated approach to solving the interoperability problem between blockchains, providing a basis for future research and development of related technologies.

12. *Atomic cross-chain asset exchange for Ethereum public chains* (Monika et al., 2021)

Is the article based on a permissioned blockchain?

No, the article is about public Ethereum testnets such as Ropsten, Kovan, Rinkeby, and Goerli.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the paper proposes an approach for atomic transfers between heterogeneous blockchains, addressing the need for interoperability between different blockchain platforms.

Does the article propose any API or make use of an existing one?

Yes, the project uses Infura, which is a suite of Ethereum APIs, to fetch data related to transactions on Ethereum networks.

Is there any proposed architecture based on blockchain?

The architecture involves smart contracts deployed on multiple Ethereum testnets, with a user interface developed as an interactive web application using HTML, CSS, Bootstrap, and React. MetaMask is used to create and access user accounts on the Ethereum blockchain.

Is any framework used or proposed?

Truffle framework is used to create project template, compile, test and deploy smart contracts on public and private blockchain networks.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The proposed methodology involves creating smart contracts called “swap contracts” to manage atomic transactions between different Ethereum blockchains. Users share off-chain information and use these smart contracts to initiate, verify, and, if necessary, refund transfers.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, interoperability is achieved through smart contracts, specifically swap contracts, which manage the atomic exchange of assets between different Ethereum networks.

Does the work use or propose a consensus protocol for interoperability?

No specific consensus protocol for interoperability was mentioned. Interoperability is managed through the smart contracts and consensus algorithms already in place on each Ethereum network.

What benefits are presented in the article?

Blockchain networks. Automation and secure execution of atomic transactions without the need for trusted third parties. Flexibility to modify and adapt the code for different exchange scenarios. Use of smart contracts and time-locks to avoid counterparty risks, which in turn refer to the possibility that one of the parties involved in a transaction does not fulfill its part of the agreement.

What deficiencies or gaps were found in the article?

The need to share private keys to verify transactions across different networks, which may be a security concern. The approach is currently limited to ether exchanges and does not cover other cryptocurrencies or digital assets. The short block times during testing may not be suitable for all real-world use cases.

The main features of this work are the use of smart contracts and time-locks to manage atomic swaps. The implementation of an interactive web application to facilitate transactions. The use of MetaMask to create and access user accounts on Ethereum. The support for several Ethereum testnets (Ropsten, Kovan, Rinkeby and Goerli). Finally, the project is available as open source, allowing modifications and extensions to test different scenarios.

13. *Decentralized cross-blockchain asset transfers* (Sigwart et al., 2021)

Is the article based on a permissioned blockchain?

The article does not specifically mention whether the blockchain is permissioned or not. However, considering that it discusses interoperability between public blockchains like Ethereum, it can be assumed that the solution is focused on public blockchains.

Does the article discuss interoperability between blockchain platforms and/or systems?

Blockchain asset transfers, ensuring that assets can be moved between different blockchains in a decentralized manner.

Does the article propose any API or make use of an existing one?

The article does not specifically mention the existence of an API.

Is there any proposed architecture based on blockchain?

The proposed architecture involves a protocol that uses proofs of transaction inclusion via Merkle proofs and blockchain relays (ETH Relay). The protocol performs asset transfers using smart contracts that verify the inclusion and successful execution of burn (BURN) and claim (CLAIM) transactions.

Is any framework used or proposed?

The article does not mention a specific framework. The proof-of-concept implementation is done using the Ethereum network and its testnets (Rinkeby and Ropsten).

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology includes defining requirements for cross-blockchain asset transfers, specifying a protocol that meets these requirements, and implementing and evaluating a proof of concept to validate the protocol.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, the proposed solution uses smart contracts to perform asset transfers between blockchains, ensuring that assets on one blockchain can be claimed on another.

Does the work use or propose a consensus protocol for interoperability?

The paper does not mention a specific consensus protocol for interoperability. It relies on proof-of-inclusion and smart contracts to verify and finalize asset transfers between blockchains.

What benefits are presented in the article?

- **Decentralization**: The solution allows asset transfers in a decentralized manner.
- **Security**: Uses inclusion proofs via Merkle proofs and blockchain relays.
- **Interoperability**: Allows the transfer of assets between different blockchains.
- **Decentralized Finalization**: Any user can finalize transfers, not depending on a single actor.

What deficiencies or gaps were found in the article?

- **Transaction costs**: The total cost of transfers can be significant due to gas consumption. Gas consumption, in blockchain contexts, refers to the amount of gas required to perform an operation or execute a transaction on a blockchain, especially on blockchains that utilize smart contracts, such as Ethereum.
- **Relay dependency**: The time required for the blockchain relay (ETH Relay) to collect information can increase the duration of transfers.
- **Necessary adaptation**: Some of the techniques mentioned, such as NiPoPoWs, require modifications to existing blockchains to be implemented.

The main features proposed in the article are:

- **Proof of inclusion**: Uses Merkle proof to verify the inclusion of transactions.
- **Proof of concept**: Proof of concept was implemented using the Ethereum Rinkeby and Ropsten testnets.
- **Decentralized finalization**: Transfer finalization does not depend on a single user or entity.
- **Quantitative analysis**: The research includes an analysis of the costs and duration of asset transfers.

14. *Performance modeling and assurance for cross-chain* (Ke et al., 2022)

Is the article based on a permissioned blockchain?

It was not specified in the text whether the blockchain is permissioned.

Does the article discuss interoperability between blockchain platforms and/or systems?

Yes, the article is about CCC, which is a type of interoperability between different blockchain platforms.

Does the article propose any API or make use of an existing one?

The article does not explicitly mention the existence of an API.

Is there any proposed architecture based on blockchain?

The proposed architecture involves a CCC queue model, specifically the M/Cox/1 model for atomic swaps and Interledger asset transfer.

Is any framework used or proposed?

The article does not mention a specific framework used.

Is any methodology used or proposed for the implementation of blockchain in the context of the article?

The methodology involves modeling and analyzing interchain communication performance using an M/Cox/1 queuing model, with the evaluation of variables such as arrival rates, service rates, and proportions of different types of communication.

Does the work use smart contracts for the interoperability of blockchain platforms?

Yes, interoperability is achieved using smart contracts (HTLC) and CCC.

Does the work use or propose a consensus protocol for interoperability?

The paper does not explicitly mention a specific consensus protocol for interoperability.

What benefits are presented in the article?

- **Interoperability between different blockchains**: Facilitates the exchange of assets and information between different blockchains.
- **Performance optimization**: The simulation shows how to tune parameters to improve the performance of interchain communication.
- **Security and efficiency**: Setting up different types of transactions for different purposes can increase efficiency and security.

What deficiencies or gaps were found in the article?

- **High cost**: The proposed model provides a solid theoretical basis for optimizing inter-blockchain communication, considering cost and performance. Simulations demonstrate the impact of the parameters and offer insights for improving the efficiency and security of inter-chain communication.