Blockchain Interoperability

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Abstract
Blockchain is one of the most disrupting technologies in recent years and has been used in several domains, such as health, supply chain and finance. In addition, organisations started integrating their blockchains with other blockchains or other external software systems. However, this is challenging for blockchain systems as interoperability is not a native design feature. Several academic and industrial efforts were performed to enable blockchain interoperability in the last years, but they were proposed for specific domain scenarios. To the best of our knowledge, there is not a general-purpose interoperability solution that enables blockchain interoperability. This research project aims to define a general-purpose blockchain interoperability framework to enable blockchain interoperability. This framework will comprise methods, guidelines, specifications and software pieces that ease interoperability between blockchains. This paper presents this research project, describing its research questions, the adopted and projected research methodologies, preliminary results and its current status.

Keywords
Distributed Ledger Technologies (DLT), blockchain, interoperability, cross-chain transactions,

1. Introduction

Blockchain is a technology that enables decentralised payments across participants without the need of a centralised trusted third-party. Furthermore, blockchain became a suitable technology for other domains besides finance, such as health, Internet of Things (IOT) and supply chain, among others. Indeed, blockchains are used on open and permissionless scenarios where security, transparency and anonymity are key requirements, but also on closed and permissioned scenarios, where user identity, authorisation and privacy are needed. In addition, organisations started to increasingly require that permissionless and permissioned blockchains interoperate with other blockchains and external software systems. This requirement represents a challenge, as blockchains are isolated information systems, and interoperability was not part of their design. In particular, organisations are required to implement data transfer, asset transfer and asset exchange scenarios. A data transfer scenario involves copying information from a source blockchain to a target blockchain. An asset transfer scenario requires the transfer of an asset (e.g. cryptocurrency) from a source blockchain to a target blockchain, while an asset exchange scenario involves the atomic exchange of assets that belong to different blockchains.

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Blockchain interoperability differs from traditional software interoperability. Blockchain systems maintain a state following rules defined by their consensus protocol, and only data that satisfy these rules may be registered on the blockchain. Therefore, enabling interoperability between blockchains implies that there must be a consensus between blockchains about the validity of the exchanged information, which is a complex challenge. Furthermore, being blockchain a decentralised system where participants need to reach finality about their results, it is challenging for this technology to access external data that can be dynamic by nature (e.g. invoking an API of an external system). Secure integration mechanisms need to be used to ensure the blockchain's consistency.

In the last years, efforts to enable blockchain interoperability were proposed with quite a success for domain specific scenarios - such as asset transfer - (e.g. Polygon PoS Bridge [1]) and between specific blockchains (e.g. Ethereum [2] and Polygon). However, to the best of our knowledge, a general-purpose interoperability solution for blockchain systems is not yet available.

This paper provides an overview of the PhD thesis's research goals, which are focused on blockchain interoperability. The paper is structured as follows: Section 2 introduces related work on blockchain interoperability. Section 3 presents the objective of this thesis and the proposed research questions. Section 4 presents the research methodologies to be used in this thesis. Section 5 describes preliminary results and contributions, while Section 6 presents the conclusions.

2. Related work

Blockchain interoperability has gained special attention in the research community in recent years, where several literature reviews analysed the state-of-the-art [3, 4]. In particular, Belchior et al. presented the most exhaustive survey [3], where they proposed categorising blockchain interoperability solutions into three categories: Public Connectors, Hyrbrid Connectors and Blockchain of Blockchains. These categories also have the following subcategories: Notary Scheme, Hash Time Lock Contracts (HTLC), Sidechains, Trusted Relays, Agnostic Protocols and Blockchain Migrators. Scheid et al. [5] and Li et al. [6] presented two examples of Notary Scheme solutions, while there are several proposals for HTLC [4]. Zendoo is an example of a Sidechain solution using Zero Knowledge Proof for cryptocurrency transfers [7]. Abebe et al. [8] presented a solution based on Trusted Relays between two blockchains, based on Hyperledger Fabric on a data exchange scenario. Liu et al. [9] presented Hyperservice, belonging to the Agnostic Protocols category, where they proposed a platform for the modelling and specifying smart contracts to enable interoperability between blockchains in an asset exchange scenario. Scheid et al. [10] proposed a Blockchain Migrator solution, defining a framework based on policies for blockchain selection. On the other hand, Blockchain of Blockchains is the most novel and least studied category [4]. Other authors provided other classifications but were less exhaustive. For example, Koens et al. [11] proposed a classification based on twelve properties, but only included Notary Scheme, Sidechains and HTLC categories.

Regarding software architecture, Jin et al. proposed a reference architecture for blockchain interoperability based on the OSI network layers [12]. In addition, Hardjono et al. proposed an interoperability architecture based on Gateways, taking the internet model as an inspiration [13].

Some formalisation of blockchain interoperability has been proposed. Kiayias et al. [14] and then Gaži et al. [15] formalized the Sidechain solution for two consensus protocols: Proof-of-Work and Proof-of-Stake. Herlihy [16] formalised the HTLC solution through game theory. Zamyatin et al. [17] proved that achieving cross-chain communication without a trusted third party is impossible. At the same time, Lafourcade and Lombard-Platet [18] showed that it is impossible to achieve interoperability between two blockchains under the classical definition of blockchain. However, if this definition is relaxed, it is possible to achieve interoperability, creating a two-in-one blockchain (i.e. a blockchain with two ledgers).

Most of the academic community had focused on enabling interoperability between non-permissioned blockchains, while a small-scale effort was put into permissioned blockchain interoperability. This effort is even less for enabling interoperability between permissioned and permissionless blockchains [4]. Abebe et al. [8] and Bradach et al. [19] provide two solutions for permissioned blockchain interoperability. Franzoni [20] and Falazi et al. [21] propose two solutions to interoperate permissioned and permissionless blockchains but do not provide cross-chain transaction validations.

On the other hand, the industry has been active in proposing solutions for blockchain interoperability. Blocknet enables blockchain interoperability based on two components: XBridge and XRouter [22]. By design, Blocknet may enable interoperability between permissioned and permissionless blockchains, but to the best of our knowledge, only permissionless blockchains are supported. ARK is a permissionless blockchain that enables blockchain interoperability by using two protocols: Specific Smart Bridge and Protocol-Agnostic Smart Bridge [23]. ARK enables interoperability between Bitcoin and Ethereum, as well as other Bitcoin-based Blockchains. Hyperledger Cactus [24], Weaver [25], and YIU [26] are three incubated projects developed by Hyperledger to achieve blockchain interoperability. Hyperledger Cactus provides a framework that business applications may use to interoperate with heterogeneous blockchains and currently supports Hyperledger Fabric [27], Hyperledger Besu [28], Corda [29] and Quorum [30]. Weaver is a Trusted Relay based solution, where each blockchain must have an IOP module and a Trusted Relay. The IOP module is responsible for cross-chain transaction verification, while the Relay is responsible for cross-blockchain communication. YIU implements the IBC (Inter-Blockchain Communication) protocol proposed by Cosmos [31] [32]. With this approach, every blockchain must have an IBC module that implements the protocol and is responsible of the connectivity and verification of cross-chain transactions. YIU currently supports Hyperledger Besu, Hyperledger Fabric and Corda. Finally, Cosmos and Polkadot [33] are two blockchain of blockchains solutions with similar behaviour. Cosmos relies on the IBC protocol to enable interoperability between blockchains and requires the interoperating blockchains to modify their source code to support the protocol. On the other hand, Polkadot uses bridges to enable interoperability between blockchains and also requires changes in the blockchain source code. Both solutions use a main blockchain that provides a consensus protocol to validate cross-blockchain transactions. Finally, Optimism [34] and Polygon PoS Bridge [1] are two examples of Sidechain solution that allows asset transfer between Ethereum and other Ethereum Virtual Machine based blockchains. In particular, Optimism enables asset transfer between Ethereum and Optimism, and vice versa, while Polygon PoS Bridge enables asset transfer between Ethereum and Polygon. Both solutions provide cross-chain transaction verification but are specific solutions for asset transfer between two specific permissionless blockchains.

Considering the existing work, blockchain interoperability has had significant advances since the first proposals, but there are still challenges to be solved. Despite the current work, there is no consensus in the scientific community about a blockchain interoperability definition nor a categorisation of the existing solutions [4]. Existing approaches are platform specific (e.g. Polygon) and do not yet provide a general-purpose interoperability solution.

3. Objective and research questions

The main objective of this PhD thesis is to provide an approach to enable interoperability between blockchain platforms for general-purpose scenarios. To this end, this PhD thesis proposes the following research questions.

RQ1: What challenges exist to enable blockchain interoperability?

RQ2: What factors need to be considered to enable blockchain interoperability?

RQ3: What approaches exist to enable blockchain interoperability?

RQ4: What challenges are not covered by the existing approaches, and how can they be addressed?

RQ5: How can a reference framework be developed to support blockchain interoperability?

RQ6: How can this framework be applied to existing blockchains?

4. Research methodology

This PhD thesis follows the Design Science research (DSR) as it constitutes a suitable methodology to reach the research goals and provide solutions to the research questions.

The DSR is an incremental process that designs and evaluates artefacts intended to solve identified organisational problems [35]. DSR uses existing knowledge (e.g. theories, frameworks, methods, methodologies) applied to existing needs of organisations and people to build new artefacts or improve existing ones in an iterative process.

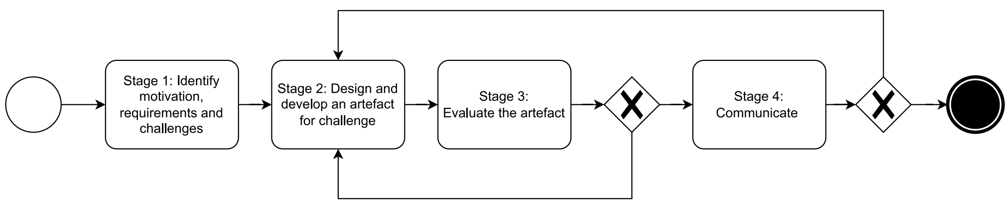

Figure 1: Proposed methodology based on Design Science Research

The followed methodology is described in Fig. 1 and is composed of four stages. At stage one, a literature review is performed to understand the motivation of blockchain interoperability, identify challenges and define the requirements of the artefact (i.e. the reference framework). Stage two takes these requirements to design the first iteration of the artefact. In stage three, the artefact is evaluated through design evaluation methods (e.g. observational, analytical, experimental). At this stage and after the evaluation of the obtained results, the process may return to stage two for the improvement of the artefact. The results are later communicated at conferences, workshops and journals at stage four, where new feedback is gathered from the research community. After this last stage is finished, the process starts again. It continues on stage two unless a defined number of iterations is reached and enables the finalisation of this PhD thesis.

Stage one is partially completed and was developed by adopting some features of the PRISMA statement [36].

We plan to execute stage two through an iterative process, following a bottom-up approach. The first iterations of the methodology will focus on the foundations of the artefact, and the following iterations will focus on building new features and its evolution.

We plan to evaluate the artefact through several evaluation methods at stage three [37]. In particular, we plan to use prototypes and illustrative scenarios to demonstrate its utility. Technical experiments, such as performance testing, will be performed to evaluate the technical performance of the artefact. An assessment through expert evaluation is planned to show the suitability of the artefact. Subject-based experiments are planned to test the artefact with different blockchains.

Finally, at stage four we plan to communicate our research results through scholarly research and professional publications. The first may include academic seminars, conferences, workshops and journals whose audience are students and researchers. The professional publications include technical reports and industry conference talks, and aims to a practitioners audience (industry and government).

5. Preliminary ideas, results and contributions

Fig. 2 depicts the expected blockchain interoperability framework as the artefact to be built. The artefact is composed of a set of elements. The theoretical concepts element describes the background concepts regarding blockchain interoperability and related concepts to understand the framework. The decision guidelines element provides decision guidelines to select the most suitable blockchain interoperability solution according to the business requirements. The design patterns element describes blockchain interoperability patterns that can be used to build a blockchain interoperability solution. The solution specification element describes a specification of a blockchain interoperability solution that enables interoperability between two or more blockchains. A reference implementation of the specification is another element that provides software following the specification. This software can be used to enable interoperability between two specific blockchains (e.g. Ethereum and Hyperledger Fabric). Finally, a set of case scenarios that shows the usage of the framework constitutes its last element.

This PhD started with stage one to answer RQ1, RQ2 and RQ3. At this stage, a literature review was performed, which analysed sixty-two papers and proposed a feature-based classification framework to improve the classification of blockchain interoperability solutions [4]. This literature review enabled the identification of challenges and requirements for developing the reference framework. Furthermore, this work constitutes the basis of the theoretical element of the framework.

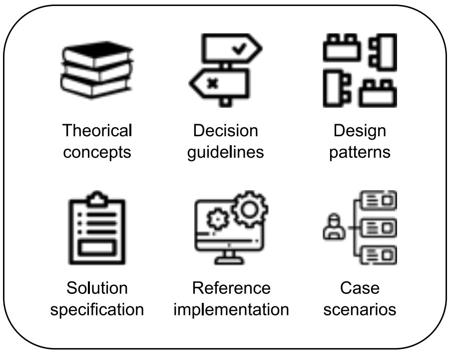

Figure 2: Blockchain interoperability reference framework

The first iteration of the methodology was finished and provided the first preliminary results, enabling interoperability between two permissioned blockchains on a specific social security scenario [19]. These results included a first version of the specification element, a prototype that served as a preliminary version of the reference implementation and an illustrative scenario that will be part of the case scenario element. The prototype and the illustrative scenario served as the evaluation methods of these results. The experiment had some limitations as it did not consider cross-chain transaction authentication, cross-chain transaction authorisation, or data privacy properties of permissioned blockchains. An extended version of this work was recently submitted to a journal where further assessment was performed based on two blockchain interoperability frameworks [38].

The ongoing work of this PhD thesis consists of starting the second iteration of the methodology and the redesign of the artefact based on the obtained results and research community feedback. The first iteration provided a tailored made interoperability solution for two specific permissioned blockchains on a specific social security scenario. The second iteration pursued the evolution of the previous elements to build a general-purpose interoperability solution. In this case, the evolution of the specification, reference implementation and case scenarios elements. Furthermore, this iteration introduced permissionless blockchains and aimed to enable interoperability between permissionless and permissioned blockchains. In particular, between Ethereum and Hyperledger Fabric. The iteration is on stage four (communication stage), where the obtained results are planned to be submitted to a workshop or conference.

On a third iteration, it is planned to start the development of the design patterns and the decision framework elements. The works of Pillai et al. will inspire the latter [39] and Belchior et al. [40] with further development.

At the end of this PhD thesis, we envision a reference blockchain interoperability framework that practitioners and researchers may use to enable interoperability between two or more blockchains. In addition, students and researchers may use the framework to get introduced to this topic and extend it with new features.

6. Conclusions

Blockchain is a disrupting technology that was applied in multiple domains (e.g. health, IOT, supply chain, art), but its usage is limited because of its design principles. Blockchains are isolated systems that work as silos of information, and interoperability is not part of their native design. It is a challenge for a blockchain to interoperate with other blockchains or other external systems. In the last years, some industrial and academic approaches enabled blockchain interoperability but they were limited to specific domain scenarios. To the best of our knowledge, there is not a general-purpose interoperability solution that enables blockchain interoperability.

This paper presents the approach of my PhD thesis, where its main objective is the development of a general-purpose interoperability framework that enables blockchain interoperability.

This PhD thesis follows a Design Science Research methodology with different stages. The first stage provided a survey on blockchain interoperability state of the art, identifying challenges and defining of the proposed research questions. Further stages enabled the development of the first elements of the artefact. The first result was a gateway-based middleware that enabled interoperability between two permissioned blockchains on a specific based scenario. These elements are being evolved in the next iterations of the methodology. In particular, the evolution to include permissionless and permissioned blockchain interoperability, cross-chain transaction authentication and new elements of the framework, like the design guidelines and design patterns.

The main contribution of this PhD thesis is the definition of a blockchain interoperability framework that provides solutions for general-purpose interoperability between blockchain platforms. Future work will include the evolution of the framework by enhancing its elements and building blocks. We envision that this framework may ease the development of blockchain interoperability solutions and positively impact their quality. In addition, this PhD thesis will provide an organised knowledge base that may be the baseline for future academic research.

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