Towards a Common Standard Framework for Blockchain Interoperability - A Position Paper

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Decentralized ledger technology (DLT) is becoming ubiquitous in today's society. After an initial grassroots adoption, enterprises embrace this technology, following the opportunity to expand to new businesses - the technology is maturing. However, organizations need to connect their existing systems and processes to blockchains (centralized - decentralized) securely and reliably, sometimes also implying to connect blockchains (decentralized - decentralized). This challenge is known as blockchain interoperability.

Blockchain interoperability comes in three modes: data transfers, asset transfers, and asset exchanges. As blockchain interoperability is still maturing, there are many unsolved challenges across the different interoperability modes. In this *position paper*, we illustrate the remaining challenges of interoperability, focusing on the systematic evaluation of interoperability mechanisms, based on the state of the art and our own experience. We first introduce the notion of cross-chain interoperability and cross-chain rules. Then, we present our survey and results.

We ran an online survey comprised of 17 items targeting blockchain specialists. Our quantitative analysis shows that several interesting metrics can show promising directions to evaluate integration solutions systematically. Finally, building upon our study, we propose the blockchain interoperability evaluation framework, the first step to evaluate blockchain interoperability solutions systematically.

Additional Key Words and Phrases: blockchain interoperability, interconnected DLT networks, cross-chain transactions, cross-blockchain communication, interoperability assessment framework

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1 INTRODUCTION

Blockchains that are isolated siloes of data and value might have a hard time competing with open systems that leverage data from multiple sources [1]. If blockchain technology seeks to become a part of the IT infrastructure of mainstream economic systems – following the natural incentives in a free market and self-regulated family of ecosystems – then blockchains need to become more interoperable. A key aspect for the successful adoption of new technology by Enterprises – including blockchain-based applications and blockchain platforms – is the ease by which these new technologies can be integrated into existing business processes. Thus, the *integration capabilities* [2, 3] of a given blockchain system will be a gating factor in its successful adoption and deployment. To promote the interoperability [1] across processes, systems, organizations, and even jurisdictions [3, 6, 7], an *interoperability framework* will be needed together with standardization efforts based on that framework for common components that will become commoditized over time. As an example, the Internet Engineering Task Force (IETF) [8] has recently embarked on this standardization road through the establishment of a new working group – called the Secure Asset Transfer Protocol

[1]for a historical perspective on interoperability, the interested reader can consult [1, 4, 5].

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(SATP) Working Group – seeking to address the challenge of reliable transfers of digital assets. This IETF effort couples a proposed common framework [7] with a general asset transfer protocol utilizing the gateway model [9].

The state of the art covers different fronts of the same problem: interoperability solutions are used to alleviate the problems of higher availability of liquidity across ecosystems (e.g., asset transfers [10, 11], bridges[12, 13]), improve user experience [14] (e.g., multi-chain wallets), data transfers across heterogeneous systems (e.g., oracles and relays [15–17], sidechains [18]), data transfers across homogeneous systems(e.g., [19–21]), identity portability (for example some solutions [22] are planned to be integrated with self-sovereign identity-based access control models [23]) and others, including improving scalability [1, 24]. For these interoperability solutions to be resilient, we need to improve their security [25, 26], privacy[27], and also processes [14]. The statement we support on in this position paper is the need for improving a *basilar process: evaluating interoperability mechanisms*. In fact, despite almost a decade of research, very few papers tackle the need for interoperability benchmarks [3, 28], or in fact, conduct benchmarks, but only for one specific solution [29].

By being able to systematically compare solutions, are we able to: 1) discern the trade-offs between solutions and therefore choose the ideal for a given use case, 2) identify faults in current systems and improve the state of the art, 3) build more resilient and secure systems, This latter aspect of security is particularly important when the year 2022 saw more than 2$B in losses due to hacks in so-called cross-chain bridges [25, 30]. Although extensive work has been done comparing and benchmarking blockchains [31, 32], there is no general consensus on how to systematically compare blockchain interoperability systems. This lack of comparative approaches very often leads to the marketing hype that dominates the industry, at the expense of actual working solutions based on robust engineering principles that benefits the entire industry as a whole. The closest to our work is [3], where the authors propose a framework for researchers to choose a blockchain interoperability solution (and therefore partially compare them). Still, they focus on high-level parameters (aim of the interoperability system, infrastructure, use case), and not on the technical details, driven by user needs.

A reasonable question to ask is what are the technical concepts that underline the evaluation of a cross-chain system? Those are two, in our view: *cross-chain transactions* [1, 25, 33], and *cross-chain rules* [25, 34]. Cross-chain transactions are a set of local transactions that realize business logic, i.e., cross-chain rules. Cross-chain rules define the sequence of transactions that should happen in more than one domain. They can be represented as datalog rules [25].

While these concepts have been introduced in the literature, we will refer to them only in the background section. From this starting point, we conduct a systematic study conducted with practitioners and academics working in the field and raise the following research questions: (1) *What are the relevant metrics to study when comparing cross-chain solutions?*, (2) *What are the relevant metrics to assess cross-chain transactions and solutions?*, and (3) *How to systematically analyze and visualize cross-chain rules?*. We contribute to the community with our survey results, its discussion, and the blockchain interoperability framework. By studying these research questions, practitioners can choose, develop, and deploy the solution with the best trade-off considering their use case (functionality, throughput, cost, and others).

This position paper is organized as follows: Section 2 presents background on the cross-chain research area. Section 3 presents our study. After that, in Section 4, we present a framework to evaluate the performance of a blockchain interoperability solution. Finally, we present suggestions for future work and conclude the paper.

2 BACKGROUND

A cross-chain transaction is a set of local transactions (happening in different chains) that are related by rules. Applications issuing cross-chain transactions to implement its business logic (or cross-chain rules) are called multiple blockchain decentralized application mDApp [35], a few examples being [36, 37]. We consider a cross-chain transaction composed of a series of atomic transactions, on different ledgers, designed to accomplish a logical unit of work [38]. The cross-chain transaction is an abstraction similar to distributed transactions in a two-phase commit system [6, 39], although other schemes can be used [40, 41]. For example, an asset transfer conducted via a cross-chain transaction is typically two transactions: one locking an asset on a source blockchain and another creating a representation of such assets in another blockchain. Although many solutions for blockchain interoperability already exist, there is a lack of supporting tools to visualize, analyze, and evaluate blockchain interoperability solutions [1]. Cross-chain transactions are distributed transactions occurring in not one, but several adversarial settings, meaning that the ACID properties from the database literature such as atomicity, consistency, isolation, and durability are more difficult to enforce.

A cross-chain rule (or cross-chain logic), i.e., the business logic a mDApp runs, is a mapping taking a set of transactions from a source ledger to a set of transactions in a target ledger, i.e., an abstraction taking a set of triggers from a system that fires a set of actions on another. Cross-chain logic tells if a set of cross-chain transactions is valid within the boundaries of a use case, which translate into local transactions on their respective blockchain (or centralized system) [25] (e.g., see the hash time-locked contract technology that implements simple cross-chain rules [42]). The execution of cross-chain logic generates a cross-chain state, which can account for and track several metrics (e.g., *performance, end-to–to-end latency, energetic consumption*). Later in this paper, we show some of our findings with regard to metrics considered desirable to measure. These measurements can provide the tools for developers to manage the life cycle of assets spawning across chains. On top of these metrics, visualization tools for cross-chain transactions could also help to analyze and infer implicit business rules. One could inspect if cross-chain logic conforms to the defined business processes - and improve those rules, similarly to common practice in the area of process mining [43]. Analysis can identify bottlenecks, paving the way to improve performance and cut costs.

Key Takeway 1. *Fundamental concepts*

The fundamental concepts in blockchain interoperability are cross-chain transactions, cross-chain rules, and cross-chain state.

3 SURVEYING THE INTEROPERABILITY COMMUNITY

We exemplify the concepts of cross-chain transactions and cross-chain rules using the Carbon Emission Application from the Carbon Accounting and Certification WG, under Linux Foundation's Hyperledger Climate Action and Accounting SIG [3, 36]. The Carbon Accounting and Certification WG aims to improve corporate carbon accounting by promoting transparency and accountability. To this end, a multiple blockchain approach is used. This use case is implemented in Hyperledger Cacti [34], an open-source blockchain interoperability project (see Figure 1). This project utilizes a permissioned network, Hyperledger Fabric (Fabric), that gathers the energy used by corporations and converts it to emissions (Rule #1). Then, these emissions are tokenized as emissions tokens on the public Ethereum network (Rule #2) so that one could trade emissions against allowances. When Rule #1 is triggered, Cacti creates Tx1 (converting the energy into emissions) on Fabric. When Rule #2 is triggered, Cacti creates Tx2 (tokenizing the emissions) on Ethereum. This combination of technologies allows maintaining some sensitive data private while publicly rewarding the participants.

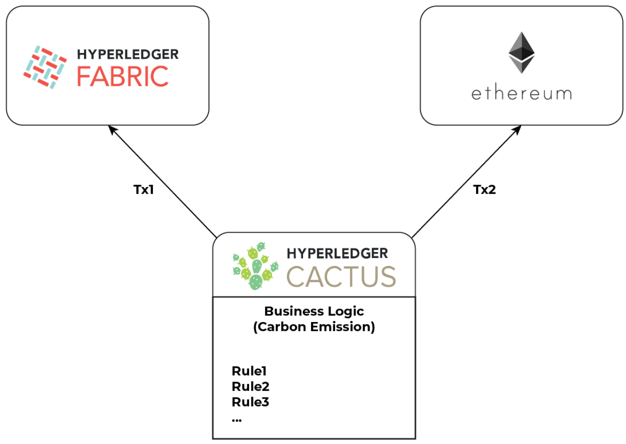

Fig. 1. System supporting cross-chain logic between two blockchains

3.1 Methodology

Analysis and visualization of cross-chain rules is a key factor for enterprise adoption of multiple DLT approaches [14]. In order to develop a better understanding of what metrics and pieces of information are the most relevant for end-users when performing cross-chain transactions and gather insight on how to visualize these transactions effectively, we used a quantitative approach through an online survey. The advantages of using online surveys - such as the "convenience of having automated data collection, which reduces researcher time and effort" [44] - are well-documented [45, 46]. Moreover, this study was conducted while the authors were involved in a Mentorship program supported by The Linux Foundation in collaboration with Hyperledger. Therefore, by leveraging this collaboration, we could reach those members of the two online communities of practice that share an interest in blockchain technology and/or blockchain interoperability. Ultimately, due to the geographical dispersion of the individuals we wanted to reach, an online survey was deemed the most appropriate method [47].

Our survey was designed following some basic rules and principles described by literature [48, 49] and administered to both experts (i.e., individuals who have developed and/or managed - running and/or maintaining - a blockchain interoperability solution) and non-expert users. It should be pointed out that participants of the latter group, although are no experts in blockchain interoperability, are still to be considered experts in the area of blockchain technology. The survey comprised 17 items (open- and closed-ended questions) and was structured into the following three main parts:

(1) collection of demographic information, e.g., experience and knowledge of blockchain technology.
(2) section on cross-chain transactions, comprising nine questions (five open-ended and four closed-ended items) and addressing aspects such as experience with multiple blockchain DApps/Apps, understanding of cross-chain logics, relevant metrics, and information needs.
(3) optional open-ended questions for additional feedback and the opportunity to provide a contact for follow-up questions.

The survey was administered online for 24 days. We shared the survey link through the official channels of the Linux Foundation and Hyperledger. A mixed approach (quantitative and qualitative) was used to analyze the data.

3.2 Results and Discussion

A total of 26 individuals participated in the survey. Most of them were software developers (n=9) and blockchain architects (n=9). The professions of the remaining respondents included academics (n=4), CEO/CTO (n=3), investor (n=3), and others (n =4). Among them, 6 out of 26 respondents (24%) are 'experts' - i.e., individuals who have developed and/or managed a blockchain interoperability solution. Most of the respondents in our sample are very experienced, with only five people having less than one year of blockchain experience. The experience of the remaining 21 individuals ranged from 2-3 years (n=6), 3-5 years (n=10), and more than 5 years (n=5). Projects developed by the expert group include protocols for verifiable data transfer between permissioned and permissionless blockchains and multi-chain payment channels. The non-experts group accounted for 76% of the population. Although a total of 26 participants may be considered a limited sample, considering that the blockchain interoperability field is in its inception, we believe that the number of responses to our survey is significant.

The survey results indicate that there is no system in production to help users track cross-chain logic or gather and view cross-chain transaction metrics, a conclusion backed up by recent research [1]. Only 5 out of 26 people (i.e., 20% of the respondents; a quite high percentage considering the novelty of the field) reported using general-purpose data traffic analysis systems (e.g., Grafana, Prometheus; to cross-analyze requests between servers) to answer this need partially. Although an excellent initial approach, the visualization could be limited to the base features of Prometheus or the other systems used. Furthermore, eight respondents reported actively gathering metrics over the cross-chain logic. Five of them further detailed their answer by reporting which metrics they gathered. These are: total transactions (2 respondents), throughput (1 respondent), transaction status (1 respondent), transaction propagation time (1 respondent), latency (1 respondent), and time consumption - execution and communication - for each step (1 respondent).

Besides exploring the current practices - which are ultimately influenced by the existing software solutions- we wanted to dive deep into the information needs of our target users. For this reason, as part of the survey section on cross-chain transactions, we have asked them:

(1) to rank a set of seven metrics, using a Likert scale from 1 (least important) to 5 (most important), depending on the relevance for their work on blockchain interoperability solutions (see Figure 2);
(2) for those ranked as 'most important', to provide a brief explanation of why such a metric is considered particularly relevant (optional); and
(3) to list additional metrics - i.e., not included in the previous question - that they would like to access and why.

The data gathered was statistically analyzed using IBM SPSS Statistics Version 28 and found reliable with α = .865. Mean, Standard Deviation (SD), and Standard Error (SE) for each of the metrics included in the survey are presented in Table 1. Except for "energy consumption" (2.65) and "carbon footprint" (2.73), all the metrics identified scored, on average, above 3 (on a 5-point scale). The average scores for end-to-end latency, end-to-end throughput, parties endorsing transactions, cross-chain logic, and total transaction fees were 3.69, 3.6, 3.5, 3.4, and 3.3. A 38% indicated that the most crucial metric is the end-to-end latency of cross-chain transactions, while 31% indicated end-to-end throughput as the most important feature. We hypothesize that the performance metrics (latency, throughput, fees) are more relevant to developers at this stage of the maturation of

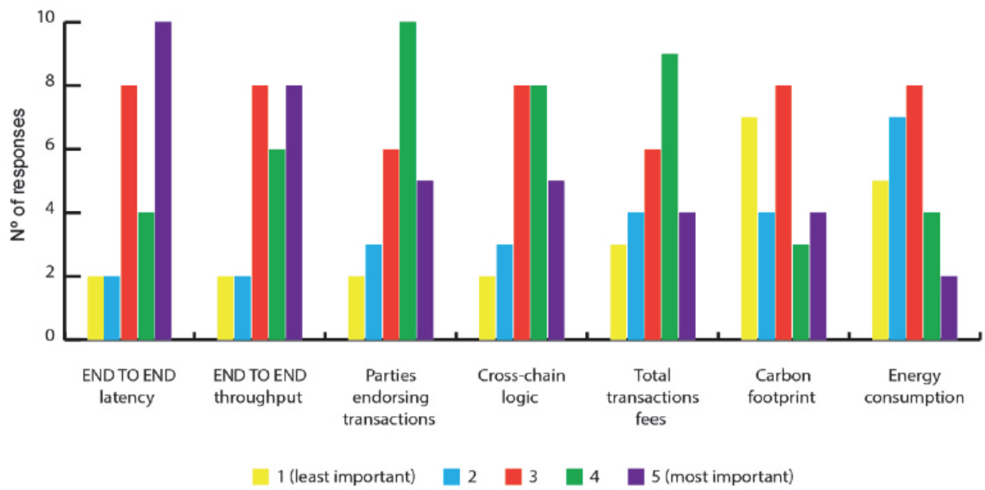

Fig. 2. Results from the survey: weighted average (1 to 5) of each proposed cross-chain transaction metric

Table 1. Mean, Standard Deviation and Standard Error of the metrics

Metric	Mean	SD	SE
end to end latency	3.69	1.289	.253
end to end throughput	3.62	1.235	.242
energy consumption	2.65	1.198	.235
carbon footprint	2.73	1.402	.275
transaction fees	3.27	1.251	.245
parties endorsing transactions	3.5	1.175	.230
crosschain logic	3.42	1.172	.230

blockchain interoperability, as opposed to qualitative metrics (energetic consumption, visualization of cross-chain logic, carbon footprint, and endorsing parties).

Around 31%, 35%, and 38% voted on parties endorsing the transaction, transaction fees, and the visualization of cross-chain rules, as their second most important metric, respectively. According to 27% of the respondents, the least important metric is the carbon footprint of cross-chain solutions.

Key Takeway 2. *Most important metrics*

Performance metrics, such as end-to-end latency, throughput, and cost (transaction fees), are currently the primary concerns for cross-chain analysis.

End-to-end latency and throughput are "what drives a better user experience which is the prerequisite of success in many cases". While qualitative metrics would be a prerequisite for a good experience for cross-blockchain middleware [6, 50, 51], performance metrics are essential since they are indicators of the security and the resilience to crashes [52] of the network (e.g., a diminishing of the throughput occurs when gateways crash) and even attacks on the interoperable mechanism [25] (in bridges, an increase in the throughput, or the change in the expected order of transactions might be indicative of an attack). A trade-off between performance, cost, and a better user experience can and should be studied. Visualizing cross-chain rules, namely the lifecycle of the cross-chain process, can provide insights into a solution's security and sound operations. For instance, a sudden decrease in the total value locked in a bridge (which would be encoded as part of the cross-chain state) could indicate an attack. Other hints could be high variance in transaction throughput or cost. This would allow understanding, for instance, if finality has been achieved for a specific cross-chain transaction (set of atomic transactions on their respective ledger).

4 FROM THEORY TO PRACTICE

In this section, we propose a simple framework to evaluate the performance of a blockchain interoperability solution based on the survey we conducted and present applications of our work.

Since a cross-chain transaction is the sum of transactions issued to their respective ledgers, their performance metrics are related to each transaction.

The upper bound for the latency of a cross-chain transaction ($\mathcal{CT}$) composed by n transactions is measured by the total latency of each transaction $(t_1, ...t_n)$, plus the coordination latency c_t, i.e., $\mathcal{CT}_t = t_1 + t_2 + ... + t_n + c_t$. Note that transactions may happen in parallel and not sequentially; therefore, the total latency might be lower than calculated. The throughput of $\mathcal{CT}$ composed of n transactions is measured by the number of cross-chain transactions per time unit. Finally, the total cost (C) of $\mathcal{CT}$ is the sum of the cost of each sub-transaction t_i, i.e., $\sum_{i=1}^{n} cost(t_i)$.

Some applications use this framework, or a variant of it. Our study yielded the first codebase version for Hephaestus[2] - a solution that builds cross-chain models from cross-chain rules and transactions, captures the metrics recommended by this work [25], as well as other projects inserted in the Hyperledger Cacti umbrella [13], and several industry products [53]. The following research paper [29] benchmarks a popular interoperability solution, IBC [1], namely it's cross-chain throughput and latency.

Visualization can use findings from research disciplines such as process mining and data mining [54], user-centered design [55], and human-computer interfaces [56]. In particular, transactions can be aggregated in cross-chain transactions, and business process model representations of the use case built [25] (see Figure 3). These models can then provide the basis for visualizing cross-chain transactions: a user can observe which step of the cross-chain flow one currently is, as well as real-time latency, throughput, and costs. For example, a token can keep track of the flow stage at all times [54], or other state tracking techniques can be used. By monitoring and visualizing cross-chain transactions, the metrics we defined enable the treatment of cross-chain state. This allows for designing increasingly complex user interfaces, data pipelines, and new services, contributing to the maturation of the technology. One specific venue is creating standardized interfaces that allow us to visualize the most important metrics according to the respondents: end-to-end latency and throughput, total transaction fees, and visualization of cross-chain rules. The API definition specified by IETF's working group SATP, which defines an interoperability protocol for asset transfers, could be a starting point [57].

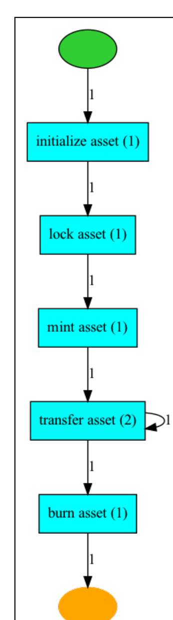

Fig. 3. Result of running Alpha Miner on cross-chain transactions referring to a bridge use case.

[2] Available under an open-source license: https://github.com/maramih/cactus/tree/ccviztx-plan

4.1 A Call to Action

Based on this simple framework, we invite researchers in the field of blockchain interoperability to follow the recommendations from the *Minimum Viable Evaluation Framework*. Future work is on empirically evaluating the existing interoperability solutions with this framework. Good candidates are Axelar, Base, Hyperlane, Optimism, LayerZero, Wormhole, Hyperledger Cacti (Node server). All solutions have bug bounties that could be eventually tracked in this assessment, varying from $250K to $2.5M. Bridge aggreagators such as Li.fi and Chainspot, as well as multi-chain APIs (Quant's Overledger or Blockdaemons Universal API, Hyperledger Cacti: Weaver Relayers and Hyperledger Cacti: Node Servers) would also be interesting to evalute.

> **Key Takeway 3.** *Minimum Viable Evaluation Framework*
>
> Blockchain interoperability solutions can be evaluated by measuring their end-to-end transaction latency, throughput, and cost, and optionally, the parties endorsing transactions (e.g., validators involved in the acceptance of a transaction to the network), carbon footprint, energetic consumption, and by defining or modeling their cross-chain logic. The experimental setup parameters and configurations should be used in the assessment. We recommend datasets, scripts, and other artefacts from the evaluation process to be made open-source, and thus assure reproducibility.

5 CONCLUSIONS AND RECOMMENDATIONS

With blockchain interoperability solutions gaining popularity in academia and industry, there is the need to conduct systematic, comprehensive evaluations that follow the same model. In this position paper, we conducted a comprehensive survey within the blockchain community to derive the parameters for a systematic evaluation of blockchain interoperability systems. Our starting point was the basilar concepts of blockchain interoperability, including cross-chain transactions, cross-chain logic, and cross-chain state. Our survey showed the potential to explore the end-to-end latency, end-to-end throughput, and cross-chain cost metrics, as well as to explore cross-chain logic as the foundation for systematic comparison of solutions.

Cost, latency and throughput will provide a foundation to compare solutions, because integration systems introduce yet another performance bottleneck to blockchains (thus measuring latency and throughput is important). Furthermore, measuring cost is important due to the operational expenses that the interoperability mechanisms have (on-chain fees, off-chain hardware, development effort). Thus, for an inteoroperabiltiy mechanism to stay competitive, a careful trade-off in these dimensions need to be made.

The collection of such metrics enables the industry and academia to create supporting tools, innovative technologies, and different evaluation frameworks. We hope that advances in this area remove barriers to the adoption of blockchain by enterprises.

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REFERENCES

[1] R. Belchior, A. Vasconcelos, S. Guerreiro, M. Correia, A Survey on Blockchain Interoperability: Past, Present, and Future Trends, ACM Computing Surveys 54 (8) (2021) 1–41. arXiv:2005.14282.
URL http://arxiv.org/abs/2005.14282

[2] E. Abebe, D. Behl, C. Govindarajan, Y. Hu, D. Karunamoorthy, P. Novotny, V. Pandit, V. Ramakrishna, C. Vecchiola, Enabling Enterprise Blockchain Interoperability with Trusted Data Transfer (Industry Track), in: Proceedings of the 20th International Middleware Conference Industrial Track, Middleware '19, Association for Computing Machinery, pp. 29–35. doi:10.1145/3366626.3368129.
URL https://doi.org/10.1145/3366626.3368129

[3] R. Belchior, L. Riley, T. Hardjono, A. Vasconcelos, M. Correia, Do You Need a Distributed Ledger Technology Interoperability Solution?doi:10.1145/3564532.
URL https://doi.org/10.1145/3564532

[4] P. Wegner, Interoperability, ACM Computing Surveys (CSUR) 28 (1) (1996) 285–287.

[5] J. Park, S. Ram, Information systems interoperability: What lies beneath?, ACM Transactions on Information Systems (TOIS) 22 (4) (2004) 595–632.

[6] R. Belchior, A. Vasconcelos, M. Correia, T. Hardjono, HERMES: Fault-Tolerant Middleware for Blockchain Interoperability, TechrXiv 14120291/1 (mar 2021). arXiv:1, doi:10.36227/TECHRXIV.14120291.V1.
URL /articles/preprint/HERMES_Fault-Tolerant_Middleware_for_Blockchain_Interoperability/14120291/1

[7] T. Hardjono, M. Hargreaves, N. Smith, V. Ramakrishna, Secure Asset Transfer (SAT) Interoperability Architecture.
URL https://datatracker.ietf.org/doc/draft-hardjono-sat-architecture

[8] IETF, IETF Home.
URL https://www.ietf.org/

[9] M. Hargreaves, T. Hardjono, R. Belchior, Secure Asset Transfer Protocol.
URL https://datatracker.ietf.org/doc/draft-hargreaves-sat-core

[10] I. Tsabary, M. Yechieli, A. Manuskin, I. Eyal, MAD-HTLC: Because HTLC is Crazy-Cheap to Attack, in: 2021 IEEE Symposium on Security and Privacy (SP), pp. 1230–1248. doi:10.1109/SP40001.2021.00080.

[11] M. Herlihy, Atomic Cross-Chain Swaps, in: Proceedings of the 2018 ACM Symposium on Principles of Distributed Computing, ACM, pp. 245–254. doi:10.1145/3212734.3212736.
URL https://dl.acm.org/doi/10.1145/3212734.3212736

[12] L2BEAT, L2BEAT – The state of the layer two ecosystem.
URL https://l2beat.com/bridges/tvl

[13] A. Augusto, R. Belchior, A. Vasconcelos, I. Kocsis, G. László, CBDC bridging between Hyperledger Fabric and permissioned EVM-based blockchains. doi:10.36227/techrxiv.21809430.v1.
URL https://www.techrxiv.org/articles/preprint/CBDC_bridging_between_Hyperledger_Fabric_and_permissioned_EVM-based_blockchains/21809430/1

[14] R. Belchior, PhD Thesis Proposal - Blockchain Interoperability, Tech. rep., Instituto Superior Técnico (sep 2021).
URL https://www.researchgate.net/publication/355370486_PhD_Thesis_Proposal

[15] J. Adler, R. Berryhill, A. Veneris, Z. Poulos, N. Veira, A. Kastania, Astraea: A Decentralized Blockchain Oracle, in: 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), pp. 1145–1152. doi:10.1109/Cybermatics_2018.2018.00207.

[16] G. Caldarelli, Understanding the Blockchain Oracle Problem: A Call for Action 11 (11) 509. doi:10.3390/info11110509.
URL https://www.mdpi.com/2078-2489/11/11/509

[17] M. Westerkamp, M. Diez, Verilay: A Verifiable Proof of Stake Chain Relay. arXiv:2201.08697.
URL http://arxiv.org/abs/2201.08697

[18] A. Singh, K. Click, R. M. Parizi, Q. Zhang, A. Dehghantanha, K.-K. R. Choo, Sidechain technologies in blockchain networks: An examination and state-of-the-art review 149 102471. doi:10.1016/j.jnca.2019.102471.
URL https://www.sciencedirect.com/science/article/pii/S1084804519303315

[19] G. Wood, Polkadot: Vision for a Heterogeneous Multi-Chain Framework.

[20] K. Jae, E. Buchman, Cosmos: A Network of Distributed Ledgers.
URL https://github.com/cosmos/cosmos/blob/7814a6cfe53873eaec1c478971d290c08ce4db7a/WHITEPAPER.md

[21] Zetachain, ZetaChain.
URL https://www.zetachain.com/

[22] E. Abebe, D. Karunamoorthy, J. Yu, Y. Hu, V. Pandit, A. Irvin, V. Ramakrishna, Verifiable Observation of Permissioned LedgersarXiv:2012.07339v2.

[23] R. Belchior, B. Putz, G. Pernul, M. Correia, A. Vasconcelos, S. Guerreiro, SSIBAC : Self-Sovereign Identity Based Access Control, in: The 3rd International Workshop on Blockchain Systems and Applications, IEEE.

[24] L. T. Thibault, T. Sarry, A. S. Hafid, Blockchain Scaling Using Rollups: A Comprehensive Survey 10 93039–93054. doi:10.1109/ACCESS.2022.3200051.

[25] R. Belchior, P. Somogyvari, J. Pfannschmid, A. Vasconcelos, M. Correia, Hephaestus: Modelling, Analysis, and Performance Evaluation of Cross-Chain Transactions. doi:10.36227/techrxiv.20718058.v1.
URL https://www.techrxiv.org/articles/preprint/Hephaestus_Modelling_Analysis_and_Performance_Evaluation_of_Cross-Chain_Transactions/20718058/1

[26] T. Haugum, B. Hoff, M. Alsadi, J. Li, Security and Privacy Challenges in Blockchain Interoperability - A Multivocal Literature Review, in: The International Conference on Evaluation and Assessment in Software Engineering 2022, ACM, pp. 347–356. doi:10.1145/3530019.3531345.
URL https://dl.acm.org/doi/10.1145/3530019.3531345

[27] D. Čapko, S. Vukmirović, N. Nedić, State of the Art of Zero-Knowledge Proofs in Blockchain, in: 2022 30th Telecommunications Forum (FOR), pp. 1–4. doi:10.1109/âĎąFOR56187.2022.9983760.

[28] N. Kannengießer, M. Pfister, M. Greulich, S. Lins, A. Sunyaev, Bridges between islands: Cross-chain technology for distributed ledger technology, Proceedings of the Annual Hawaii International Conference on System Sciences 2020-January (2020) 5298–5307. doi:10.24251/HICSS.2020.652.

[29] J. O. Chervinski, D. Kreutz, X. Xu, J. Yu, Analyzing the performance of the inter-blockchain communication protocol (3 2023).
URL https://arxiv.org/abs/2303.10844v2

[30] S.-S. Lee, A. Murashkin, M. Derka, J. Gorzny, SoK: Not Quite Water Under the Bridge: Review of Cross-Chain Bridge Hacks. arXiv:2210.16209, doi:10.48550/arXiv.2210.16209.
URL http://arxiv.org/abs/2210.16209

[31] T. T. A. Dinh, J. Wang, G. Chen, R. Liu, B. C. Ooi, K.-L. Tan, BLOCKBENCH: A Framework for Analyzing Private Blockchains, in: Proceedings of the 2017 ACM International Conference on Management of Data, SIGMOD '17, Association for Computing Machinery, pp. 1085–1100. doi:10.1145/3035918.3064033.
URL https://doi.org/10.1145/3035918.3064033

[32] R. Wang, K. Ye, C.-Z. Xu, Performance Benchmarking and Optimization for Blockchain Systems: A Survey, in: J. Joshi, S. Nepal, Q. Zhang, L.-J. Zhang (Eds.), Blockchain – ICBC 2019, Lecture Notes in Computer Science, Springer International Publishing, pp. 171–185. doi:10.1007/978-3-030-23404-1_12.

[33] M. Herlihy, B. Liskov, L. Shrira, Cross-chain deals and adversarial commerce 31 (6) 1291–1309. doi:10.1007/s00778-021-00686-1.
URL https://doi.org/10.1007/s00778-021-00686-1

[34] H. Montgomery, H. Borne-Pons, J. Hamilton, M. Bowman, P. Somogyvari, S. Fujimoto, T. Takeuchi, T. Kuhrt, R. Belchior, Hyperledger Cactus Whitepaper.
URL https://github.com/hyperledger/cactus/blob/master/docs/whitepaper/whitepaper.md

[35] G. Verdian, P. Tasca, C. Paterson, G. Mondelli, Quant Overledger Whitepaper v0.1.

[36] Carbon Emission Working Group, Hyperledger Working Groups - Blockchain Carbon Accounting.
URL https://github.com/hyperledger-labs/blockchain-carbon-accounting

[37] L. Riley, Universal DLT interoperability is now a practical reality – Hyperledger Foundation.
URL https://www.hyperledger.org/blog/2021/05/10/universal-dlt-interoperability-is-now-a-practical-reality

[38] D. Avrilionis, T. Hardjono, Towards Blockchain-enabled Open Architectures for Scalable Digital Asset Platforms. arXiv:2110.12553, doi:10.48550/arXiv.2110.12553.
URL http://arxiv.org/abs/2110.12553

[39] R. Belchior, A. Vasconcelos, M. Correia, T. Hardjono, Enabling Cross-Jurisdiction Digital Asset Transfer, in: IEEE International Conference on Services Computing, IEEE, 2021.

[40] P. Robinson, R. Ramesh, S. Johnson, Atomic Crosschain Transactions for Ethereum Private Sidechains 3 (1) 100030. doi:10.1016/j.bcra.2021.100030.
URL https://www.sciencedirect.com/science/article/pii/S2096720921000257

[41] A. Zamyatin, D. Harz, J. Lind, P. Panayiotou, A. Gervais, W. Knottenbelt, XCLAIM: Trustless, Interoperable, Cryptocurrency-Backed Assets, in: 2019 IEEE Symposium on Security and Privacy (SP), pp. 193–210. doi:10.1109/SP.2019.00085.

[42] K. Narayanam, V. Ramakrishna, D. Vinayagamurthy, S. Nishad, Atomic cross-chain exchanges of shared assetsdoi:10.48550/arXiv.2202.12855.
URL https://ui.adsabs.harvard.edu/abs/2022arXiv220212855N

[43] W. M. P. van der Aalst, Conformance Checking, in: W. M. P. van der Aalst (Ed.), Process Mining: Discovery, Conformance and Enhancement of Business Processes, Springer, pp. 191–213. doi:10.1007/978-3-642-19345-3_7.

URL https://doi.org/10.1007/978-3-642-19345-3_7
[44] K. B. Wright, Researching internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services, Journal of computer-mediated communication 10 (3) (2005) JCMC1034.
[45] W. Wiersma, The validity of surveys: Online and offline, Oxf. Internet Inst 18 (3) (2013) 321–340.
[46] D. A. Dillman, Mail and internet surveys: The tailored design method (2007).
[47] C. Van Mol, Improving web survey efficiency: the impact of an extra reminder and reminder content on web survey response, International Journal of social research Methodology 20 (4) (2017) 317–327.
[48] P. M. Boynton, T. Greenhalgh, Selecting, designing, and developing your questionnaire, Bmj 328 (7451) (2004) 1312–1315.
[49] A. N. Oppenheim, Questionnaire design, interviewing and attitude measurement, Bloomsbury Publishing, 2000.
[50] Quant Foundation, Overledger Network Whitepaper v0.3, Tech. rep., Quant (2019).
[51] M. Hargreaves, T. Hardjono, R. Belchior, Open Digital Asset Protocol draft 02, Internet-Draft draft-hargreaves-odap-02, Internet Engineering Task Force (2021).
URL https://datatracker.ietf.org/doc/html/draft-hargreaves-odap-02
[52] R. Belchior, M. Correia, T. Hardjono, DLT Gateway Crash Recovery Mechanism draft 02, Internet-Draft draft-belchior-gateway-recovery-02, Internet Engineering Task Force (2021).
URL https://datatracker.ietf.org/doc/html/draft-belchior-gateway-recovery-02
[53] Cryptos In Cross-chain Category.
URL https://www.coinlore.com/crypto/cross-chain
[54] W. Van Der Aalst, Process mining: Overview and opportunities, ACM Transactions on Management Information Systems (TMIS) 3 (2) (2012) 1–17.
[55] P. F. Campos, N. J. Nunes, Canonsketch: a user-centered tool for canonical abstract prototyping, in: Engineering Human Computer Interaction and Interactive Systems: Joint Working Conferences EHCI-DSVIS 2004, Hamburg, Germany, July 11-13, 2004, Revised Selected Papers, Springer, 2005, pp. 146–163.
[56] S. Scuri, G. Tasheva, L. Barros, N. J. Nunes, An hci perspective on distributed ledger technologies for peer-to-peer energy trading, in: Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part III 17, Springer, 2019, pp. 91–111.
[57] M. Hargreaves, T. Hardjono, R. Belchior, Secure Asset Transfer Protocol (SATP).
URL https://datatracker.ietf.org/doc/draft-hargreaves-sat-core