Blockchain Usage in Smart Cities: A Systematic Review

Stefano Loss, Nélio Cacho, Frederico Lopes

[1]Federal University of Rio Grande do Norte, Natal, Brazil.

momoloss10@gmail.com, neliocacho@dimap.ufrn.br, fred@imd.ufrn.br

Abstract. *Blockchain has been widely used to store decentralized and secure cryptocurrency transactions (for instance, Bitcoin solution). On the other hand, smart city applications are concerned with how data and services can be stored and shared securely. In this regard, this paper investigates the use of blockchain in the context of smart city environments. We conducted a systematic review to understand how blockchain could be used in smart city scenarios. This review resulted in a set of important requirements to meet the needs of the blockchain in the context of smart cities.*

1. Introduction

Bitcoin was initially described in 2008 in the article ”Bitcoin: A Peer-to-Peer Electronic Cash System” by the pseudonym Satoshi Nakamoto [Rull Aixa]. The creation of blockchain is inherent in the creation of Bitcoin. The blockchain can be defined as a distributed database that registers an ordered list of transaction records that are immutably linked together through a chain of blocks. With Bitcoin's popularization, several applications began to use blockchain to store data in a distributed way. According to David Aixa, some potential blockchain applications are supply chain, digital identity, voting, healthcare, and government [Rull Aixa , p. 37]. Some aim to solve social problems in the most diverse areas, contributing to the construction of smart cities. While Smart Cities infuse ”information into its physical infrastructure to improve conveniences, facilitate mobility, add efficiencies, [...] identify problems and fix them quickly, recover rapidly from disasters, collect data to make better decisions and deploy resources effectively, and share data to enable collaboration across entities and domains” [Moss Kanter and Litow 2009].

Thus, in the Smart City environments perspective, blockchain can share data and services transparent, secure, and reliable, enabling the integration of city services to improve the population's quality of life [Sun et al. 2016]. In this context, this work shows how blockchain can be used in Smart City environments. To achieve this goal, we conduct a systematic review to allow a better understanding of how blockchain could contribute to developing reliable solutions. This paper is organized as follows. Section 2 presents the stages of the systematic review: planning, execution results, requirements taxonomy, and threats to validity. Finally, Section 3 presents final remarks and future work.

2. Systematic Review

This systematic review is divided into four steps, based on the guidelines provided by [Kitchenham 2004], as follows: **1) Planning** to define the search criteria and the inclusion and exclusion criteria to collect related works for blockchain usage in the context of Smart Cities; **2) Execution** - to perform a search for the primary studies (i.e., papers, conference publications, periodicals) applying the inclusion and exclusion criteria to filter the results that were relevant to this review; **3) Requirements Taxonomy** to define of the relevant requirements for this study; **4) Evaluation Results** - to extract of data from the search results to formulate the answers for the research questions. The following subsections explain how each one of these steps was performed.

2.1. Planning

This step of the systematic review defines **Research Questions (RQ)** to discover the primary studies that present some information about blockchain usage in Smart Cities environments. *RQ1*: How can Blockchain be used in Smart Cities environments? and *RQ2*: How can Blockchain be used in systems integration?; **Search Strategies** to find studies related to the research questions, we have chosen the following keywords or synonyms for these keywords to form search strings: *("Interoperability" OR "interoperate" OR "interoperable" OR "interoperation" OR "integrate" OR "integration") AND ("Blockchain" OR "Ethereum") AND ("Smart Cities" OR "Smart City")*; This string was adapted for each database in IEEE Xplorer, ACM Digital Library, and Scholar Google repositories.

Inclusion Criteria (CI) was used to include relevant studies in this systematic review, namely: *CI1* - The study proposes, exemplifies, or evaluates the use of Blockchain in the context of Smart Cities. *CI2* - The study proposes, exemplifies, or evaluates the use of Blockchain in a System of Systems context. **Exclusion criteria (EC)** was used to exclude studies with no relevance for this review (studies that do not contribute to answering RQ1 or RQ2). The ECs are: *EC1*: The study is not related to Systems Integration or Smart Cities; *EC2:* The study is not in English; *EC3*: The study does not have an abstract, or the full text is not available; *EC4*: The study consists of a compilation of studies from conferences or workshops, for example; *EC5*: The study was written before 2017. The studies selected for this systematic review are defined as those that satisfy at least one of the inclusion criteria and do not satisfy any of the exclusion criteria.

2.2. Execution Results

After completing the searches, we read their titles, keywords, and abstract to decide which ones would be filtered and selected to be read. Only papers whose abstracts and keywords evidenced that they are related to our systematic review were selected to be fully read. From 31 papers found by the ACM Digital Library search engine, 15 were filtered, and 5 were selected for the second stage; from 22 found by the IEEExplorer search engine, 10 were filtered, and 4 were selected for the second stage; from 72 papers found by the Scholar Google search engine, 36 were filtered, and 11 were selected for the second stage. In total, it was selected 20 relevant papers for our study, as listed in Selected Papers table `https://drive.google.com/file/d/17I64plyowvWB9yfLQE_gLk3Fvh7KmY8K/view?usp=share_link`. That table shows the identification, author, title, and year of each selected paper, and such information will be used to refer to these studies in the following sections.

2.3. Requirements Taxonomy

According to the paper's analysis results, we identify some blockchain requirements in the context of smart cities. Table 1 lists the complete requirements found by our systematic review. In the following few paragraphs, we define each requirement and discuss its importance to the blockchain in the context of smart cities. **Security** is "a composite of the attributes of confidentiality, integrity, and availability" [Avizienis et al. 2004].

Blockchain uses cryptography to protect data via many protection mechanisms. For example, it can use authentication of communicating parties/messages, the confidentiality of secret keys. **Privacy** is needed since some transaction data should be private and accessible only by authorized participants.

Data Sharing is ”the transmission of bulk data to other institutions [...] forces institutions to yield operational control of their data” [Peterson et al. 2016]. As blockchain is a decentralized database, it should share, replicate and synchronize all data among network members. This fact could be challenging since each transaction must be logged simultaneously in multiple places. **Decentralized** requirement ”is necessary in order to ensure the involvement of many actors in the same network and guarantee full transparency and reliability between people who do not know each other” [Pinna and Ibba 2017]. The blockchain can not approve transactions or set specific rules to accept transactions. All the participants in the network have to reach a consensus to accept transactions.

Resilience is served by the **fault tolerance** mechanism present in Blockchain's technology. A System is resilient when protected against the faults that might affect it [Avizienis et al. 2004]. Smart Cities solutions must be resilient enough to sustain data availability even at high requests by their applications/clients. Since blockchain has a decentralized database, if one blockchain node becomes inaccessible, it is possible to access the transaction data from another node. **Reliability** is the continuity of executing a service correctly [Avizienis et al. 2004]. Due to blockchain's decentralized nature, a failure of a single peer (node) should not affect the operation of the rest of the network. ”This avoids the single point of failure and ensures the high reliability of applications that are based on blockchain technology” [Chen et al. 2018]. **Immutability/Data Integrity/Consistency** is the fact that data cannot be edited after being stored. In the blockchain transaction, data cannot be altered/updated once it uses cryptography, hashing, and decentralized structure to protect it, making it impossible to change the data after being inserted. Furthermore, the data stored in the blockchain should be validated by the rest of the blockchain network.

Traceability / Historical Data is the ability to perform a ”trace back verification of all the identity instances available in the block” [Abbasi and Khan 2017]. Blockchain should be capable of accessing all historical data stored at the transactions, making it possible to track data and verify any information. **Scalability**, in the blockchain context, for [Kakavand et al. 2017] is the increase of I) **Number of nodes**: system performance changes as the number of nodes changes; ii) **Number of transactions**: system performance changes as the number of transaction submissions per second changes; iii) **Number of users**: system performance changes as the number of active users submitting transactions changes; iv) **Geographic dispersion**: system performance changes as the geographic dispersion of nodes changes.

Interoperability refers to the capacity of various IT systems and software applications to interact, share data, and utilize shared information. Blockchain should share data and services with IT systems, allowing interoperability between such computational solutions. **Transparency** the fact that ”all blockchain network exchanges are cleared in the blockchain, which means a total, verifiable and unchanging record of any action exists” [Sharma et al. 2017]. Blockchain should ensure that all transactions are viewed and could be scanned by all nodes in the network, presenting the transparency desired by Smart City applications, even with some private information. **Smart Contracts** are used to allow trusted transactions without third parties. ”It contains code functions and can interact with other contracts, make decisions, store data [Sun et al. 2016]”. Blockchain should use Smart Contracts as a way to provide automatically validated transactions.

2.4. Evaluation Results

Table 1 shows how each of those 20 selected papers relates to each requirement. In this direction, we defined the possible grades to specify how each paper covers the requirements: grade 0 (zero) if the study does not mention the requirement; grade 1 (one) if the study only mentions the requirement, without any explanation; grade 2 (two) if the study explains the importance of the requirement; and grade 3 (three) if the study describes how the authors implement the requirement. To give an ordered classification of the list of selected articles, we graduate for each requirement to reach a final grade for each paper, considering that all requirements have the same weight.

Table 1. Requirements Taxonomy

Requirements	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
Security	3	1	3	1	2	2	3	3	3	2	3	3	3	3	3	2	3	2	2	3
Privacy	2	1	2	1	0	1	2	2	2	1	2	2	3	2	2	2	1	3	2	2
Data Sharing	1	0	0	1	1	1	1	0	2	1	1	1	1	1	1	1	1	1	1	1
Decentralized Access	2	1	2	1	0	1	2	1	0	0	2	0	2	2	0	1	1	2	0	2
Resilient	0	0	1	0	1	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0
Immutability	2	1	0	1	1	2	2	1	0	0	2	1	1	0	1	1	1	0	1	1
Data Integrity/Consistency	1	1	0	0	1	1	1	0	1	1	2	1	3	0	0	1	0	1	1	1
Traceability/Historical Data	2	1	2	1	0	1	1	0	2	1	0	0	1	0	0	1	1	0	0	0
Scalability	0	1	0	0	1	0	2	1	0	0	2	2	2	1	1	1	0	0	2	1
Interoperability	0	1	0	1	2	0	1	1	2	0	2	1	2	0	0	0	0	1	3	0
Transparency	1	1	0	1	0	0	1	1	0	0	1	0	1	1	0	2	1	1	0	1
Reliability	2	1	0	0	1	1	1	1	2	1	1	1	1	0	0	1	1	0	1	0
Smart Contract	2	1	2	2	1	0	3	1	3	1	2	2	2	1	1	2	1	1	1	1
Total	**18**	**11**	**12**	**10**	**11**	**10**	**22**	**12**	**17**	**8**	**21**	**15**	**22**	**11**	**9**	**15**	**12**	**12**	**14**	**13**

Education is the theme of S1. This paper explores the potential of blockchain for education applications. ”It (Blockchain) can store a complete, trustworthy set of records of educational activities, including the processes and results informal and informal learning environments. It can also record teachers’ teaching behaviors and performance, thus providing a reference for teaching evaluation” [Chen et al. 2018].

Papers S2, S12, and S18 adopt blockchain to store health data. At the same time, S2 is concerned with data sharing securely, allowing third parties to use electronic health record data to provide data interoperability. S12 proposes a mobile app called Healthcare Data Gateway to store medical records with personalized access for patients without compromising privacy. On the other hand, S18 uses blockchain, fog computation, and IoT to enable efficient and smart diagnosis, supervision, and treatment of medical conditions.

Security is the theme of S3, S8, and S20. S3 uses Blockchain technology as a platform for the safety and reliability of data sharing. This solution can promote trusted information, quality data, and security in a viable and reliable way. S8 proposes a conceptual architecture for securing a smart city using blockchain technology. Finally, S20 is concerned about using blockchain to enable all devices to connect safely in a distributed setting with resistance to several attacks and privacy issues.

Solutions involving the Internet of Things (IoT) are presented in S5, S7, S9, S11, S13, and S14. A blockchain-based Smart City infrastructure has been proposed by S5, with the advantages of increased efficiency due to interactions with IoT sensors, optimized distribution of resources, and fraud reduction. At the same time, S7 presents a review of the role of blockchain in enabling IoT-based smart cities. In contrast, S9 proposed applying blockchain technology to the smart city and its trust infrastructure by combining its network and data architecture. Another theoretical paper is S11 which discussed several vital factors for converging Blockchain and AI technologies to help form a sustainable, innovative society. It also summarizes the key points that can be used for developing various blockchain-AI-based intelligent systems.

In contrast, S14 introduces the IBchain, a new blockchain architecture with the IoT. Data from sensors and microchips are processed by blockchain nodes, making them more portable and relevant for immediate conversations. In IBchain methodology, the smart objects can connect securely with other smart objects making possible secure communication among the smart devices. Finally, S13 proposes a hierarchical blockchain-based platform for ensuring the integrity of smart cities IoT data and blockchain interoperability. Through the integration of transactions among different smart city organizations into Blockchain-of-blockchains (BoBs), for ensuring data integrity and blockchain interoperability simultaneously. It solves IoT data integrity and interoperability issues of heterogeneous blockchain platforms.

The supply chain using blockchain is presented in S6 and S10. These studies use blockchain to verify, authorize and control each transaction between a seller and buyer in a supply chain. S6 aims to impact the process cost by cutting time in order processing and reducing inventory space with better tracking and logistics in smart cities. S10 developed a smart city model that applies blockchain technology to promote the organizational structure of the information transmission alliance using the blockchain and to organize smart services by promoting the integration of smart solutions.

Articles S16, S17, and S19 are about governance. While S16 is a theoretical paper that presents the blockchain benefits ins governance once it can be used to raise the decision-making process, creating a sense of trust, transparency, and security between citizens and governments. In contrast, S17 presents a framework for sustainably integrating a city's resource management infrastructure based on their needs and enhanced environmental monitoring. S19 proposes a framework for interoperability across various blockchain-based smart city services facilitating governance.

Artificial Intelligence (AI) is used in a blockchain-based IoT framework in S15. It presents the integration of AI and blockchain for IoT applications. The experimental analysis presents the efficiency of the proposed architecture in terms of accuracy, latency, security, and privacy. Already S4 proposes a solution using Blockchain technology to join the Energy Grid, exchange information, and buy/sell energy between the involved nodes (energy providers and private citizens) using the blockchain granting ledger.

In the last line of Table 1, there is the total sum of the scores assigned to each requirement for each paper. Although all papers present a solution for Smart Cities using blockchain as a technological solution. Studies S7, S11, and S13 (with higher grades in the total sum) were concerned with presenting the justification for most of the requirements. In contrast, other articles were only concerned with presenting the blockchain and showing how the blockchain was used in the proposed solution by each paper.

3. Conclusion and Future Work

We believe that blockchain technology has much to contribute to smart city solutions once it enables the creation of solutions in distributed networks to meet the demand of the entire blockchain. This work presented a systematic review of how blockchain can be used in smart city environments. In addition, a requirements taxonomy has elicited a set of requirements needed to use Blockchain in Smart Cities and discover the leading platforms used in this context. In future work, propose and implement a new platform architecture to fulfill these requirements to share data and services between diverse solutions in Smart Cities. Making it possible to turn public services smarter and enhance the quality of life for citizens.

ACKNOWLEDGMENT

This work is supported by Smart Metropolis Project[1] and CNPq.

References

Abbasi, A. G. and Khan, Z. (2017). Veidblock: Verifiable identity using blockchain and ledger in a software defined network. In *Companion Proceedings of the10th International Conference on Utility and Cloud Computing*, pages 173–179. ACM.

Avizienis, A., Laprie, J.-C., Randell, B., and Landwehr, C. (2004). Basic concepts and taxonomy of dependable and secure computing. *IEEE transactions on dependable and secure computing*, 1(1):11–33.

Chen, G., Xu, B., Lu, M., and Chen, N.-S. (2018). Exploring blockchain technology and its potential applications for education. *Smart Learning Environments*, 5(1):1.

Kakavand, H., Kost De Sevres, N., and Chilton, B. (2017). The blockchain revolution: An analysis of regulation and technology related to distributed ledger technologies.

Kitchenham, B. (2004). Procedures for performing systematic reviews. *Keele, UK, Keele University*, 33(2004):1–26.

Moss Kanter, R. and Litow, S. S. (2009). Informed and interconnected: A manifesto for smarter cities.

Peterson, K., Deeduvanu, R., Kanjamala, P., and Boles, K. (2016). A blockchain-based approach to health information exchange networks. In *Proc. NIST Workshop Blockchain Healthcare*, volume 1, pages 1–10.

Pinna, A. and Ibba, S. (2017). A blockchain-based decentralized system for proper handling of temporary employment contracts. *arXiv preprint arXiv:1711.09758*.

Rull Aixa, D. Analysis and study of data security in the internet of things paradigm from a blockchain technology approach.

Sharma, P. K., Moon, S. Y., and Park, J. H. (2017). Block-vn: A distributed blockchain based vehicular network architecture in smart city. *Journal of Information Processing Systems*, 13(1):84.

Sun, J., Yan, J., and Zhang, K. Z. (2016). Blockchain-based sharing services: What blockchain technology can contribute to smart cities. *Financial Innovation*, 2(1):26.

[1] https://smlab.imd.ufrn.br/