Architecting Blockchain Systems: A Systematic Literature Review

Gregory Fournier
Polytechnique Montreal
Montreal, Canada
gregory.fournier@protonmail.com

Fabio Petrillo
Université du Québec à Chicoutimi (UQAC)
Chicoutimi, Canada
fabio@petrillo.com

ABSTRACT

Companies are gravitating more and more towards the use of blockchains in their systems, but it is not a silver bullet. Challenges are currently holding back blockchain's enormous potential, such as scalability issues and frustrating trade-offs, most notably in public decentralized blockchain systems. In this paper, we conduct a Systematic Review of Literature in order to explore the current challenges of blockchains while presenting possible solutions to each of these challenges. We conclude that current challenges can be summarized in three categories: Scalability issues, security issues and a choice of the consensus protocol. We also briefly discuss the use of blockchain in current systems, concluding that while blockchains current immaturity makes it hard to recommend for most projects, blockchains in their current state could be used in the Internet of Things.

CCS CONCEPTS

• **Software and its engineering → Software architectures**.

KEYWORDS

Blockchain, bitcoin, crytpocurrency, scalability, security, consensus protocol

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1 INTRODUCTION

Ever since the rise of bitcoin, the blockchain as a data structure has become more and more popular. Companies are eagerly looking to use blockchains outside the world of cryptocurrencies to replace current data structures or for future endeavours. Blockchain's fundamental property of maintaining immutable information is very enticing for companies who wish to defer malicious users from tampering with data. However, since blockchains are a rather new subject, there exists little material on architecting and designing software with blockchains compared to more traditional data structures. The challenges behind implementing or integrating a blockchain are not always emphasized, which are important motivators for this paper.

The objective of this systematic review is to present the various challenges of architecting and implementing blockchains. By extracting popular trends and useful findings amongst the existing papers on architecting blockchain systems, this paper can serve as a guide for future architects who wish to inform themselves before designing their system efficiently. Rather than focusing on one problem or solution, this paper seeks to give readers a brief overview of current challenges concerning blockchains. The research question is thus **Q1: What are the current challenges behind architecting and implementing blockchain systems?** As a side question, based on the results of the previous question, answering the following question: **Q1.1 briefly: Should companies adopt the blockchain considering its current state of affairs?**

Section 2 gives basic information about blockchains in order to understand the rest of the paper, while shortly discussing related works. Section 3 discusses the strategy used in order to obtain the final papers that were reviewed. Section 4 discusses the main ideas that stood out in the initial review of the papers. Sections 5, **??**, and 6 answer research question **Q1** while section 7 answers question **Q1.1**. Finally, section 8 concludes the paper with the threats to validity and possible future work.

2 BACKGROUND

A *blockchain* is a basic data structure first proposed by Satoshi Nakamoto in 2008 for the peer-to-peer currency known as *Bitcoin* [31]. A blockchain is composed of many blocks, which can contain any type of data, though they are most often used to keep a record of various transactions between peers. These blocks are linked together backwards, and each block verifies the integrity of its previous block through its hash. Tampering with a previous block will invalidate its hash, making it easily noticeable. Calculating a new hash, also known as *mining* is a very demanding process, and the modification of one block has an effect on every younger block linked to it. While mining is very difficult, verifying the validity of a mined block is very easy for peers. This property of blockchains deters malicious users from modifying block data to their advantage.

Mining blocks is a CPU-intensive task. As such, users who mine (*miners*) are compensated for their work. This is commonly referred to as *Proof-of-Work*. However, as it will be discussed further on, Proof-of-Work is not the only consensus protocol.

In a *distributed blockchain*, such as bitcoin, every peer contains a copy of the complete blockchain, and several of those peers contribute to the addition of new blocks through mining. The peers also serve as judges, working together to ensure the validity and

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integrity of the blockchain. Blockchains can be distributed (peer-to-peer), decentralized (not one but several points where data is transfered), and centralized (one central point of data transfer).

One of the motivations in creating the blockchain was to mitigate a common problem with distributed currencies proposals known as the *Double Spending Attack*. In a Double Spending Attack, a user is able to use an amount of currency two times, enabling him to essentially obtain twice the value of the currency spent. In a traditional centralized monetary system such as a bank, all transactions are validated by the same entity, the central bank. However, in a distributed monetary system, each and every peer can potentially validate a transaction, providing the opportunity for an attacker to make the same transaction twice and have it validated by two different peers, one being himself. Further explanation and discussion of double attacks can be found in section **??**

The current bitcoin policy in accepting new blocks on the blockchain prevents malicious users from effecting a double spending attack, as long as the user owns less than 51% of the blockchains computing power.

These various properties of blockchains vastly reduce the possibility of hiding a tampered block by *remining* its hash value and assigning it to the correct blocks, as to attack one block a malicious user must rehash the desired block as well as every younger block linked to it. Thus, blockchains are very useful when immutability is a desired property, as long as pseudonymity is sufficient for the end users.

The most popular use of blockchain is without a doubt bitcoin, the most popular cryptocurrency which debuted the rapidly augmenting interest in blockchains and cryptocurrencies. However, there exists others besides crytocurrencies who are using blockchains, such as **Ring**, a communication platform[38].

2.1 Related works

A Taxonomy of Blockchain-Based Systems for Architecture Design regroups many important dimensions and categories for classifying blockchains and ways of using them in systems.[49] The researchers divide decision making into three main categories: architectural design regarding decentralisation, architectural design regarding storage and computation and architectural design regarding blockchain configuration. This paper gives insight on how reparametrization can solve certain issues. However, further research concludes that while reparametrization can mitigate certain scalability issues, their use should only be considered as a short term solution, as we quickly come to a point where modifying blockchain parameters can no longer be beneficial due to existing network and computing issues.

An overview of blockchain technology: Architecture, consensus, and future trends, *Blockchain Challenges and Opportunities: A Survey* and *Blockchain for the Internet of Things: a Systematic Literature Review* are also very interesting papers which explore the different challenges of blockchains. While these papers explore in depth one or two issues, this paper aims to combine these information in addition to other findings, and focus more on the different possible solutions currently available to each problem as of now [50][51][7].

Table 1: Overall Paper Subject Distribution Concerning Challenges and Solutions

Topic	Papers	Total
Scalability	[51][15][40][45][13] [2][50][48][29][25][9] [32][1][18][10][49][8] [46][33][23][43][20][28][41]	24
Security	[51][22][50][48] [42] [17][9][1] [18][7][10] [49][19][14][26][39][4] [43][20][37][12][11]	22
Consensus Protocol	[15][40][45] [30] [22][3][34][29][25][1] [10][19][26]	13
Other	[9][6][44][47][33][24][21][5][35] [36][27]	11

3 METHODOLOGY

3.1 Data source

3.1.1 Initial Source. In order to assess the feasibility of a systematic review on blockchain architecture, an initial study of 3 key papers was done[7][10][49]. Once the pertinence of this paper was established, a search was done with the query *"(architect* OR design*) AND blockchain AND system*"* which yielded 163 papers.

3.1.2 Impurity Removal and Application of Selection Criteria. The 70 top papers were analyzed, of which 20 papers were retained based on their title and credibility. Credibility was determined by number of citations per year and total amount of citations. Selection criteria favoured papers that pointed out things such as problems, issues, challenges, and solutions to these aforementioned problems, but we also looked for generalized papers on blockchain architecture and papers discussing the use of blockchains besides crytocurrency.

3.1.3 Forward Snowballing. Finally, forward snowballing was done on the two most valuable papers. Since *A Taxonomy of Blockchain-Based Systems for Architecture Design* is a main pivot point of this paper, forward snowballing was done on this paper and on *Bitcoin-NG: A Scalable Blockchain Protocol*. 28 papers were kept from this snowballing. Overall, 48 papers have been retained for systematic review.

3.2 Tools

Publish or Perish was used for researching, refining queries, and keeping a tab on what articles were retained for study[16].

4 PRELIMINARY RESULTS

Of the 48 retained articles, 24 articles either pointed out the difficulties concerning blockchain scalability or offered possible solutions. Scalability is in fact one of the biggest constraints currently holding back blockchains. Most papers discuss the current limitations in the bitcoin protocol which limits its possibility of scaling via

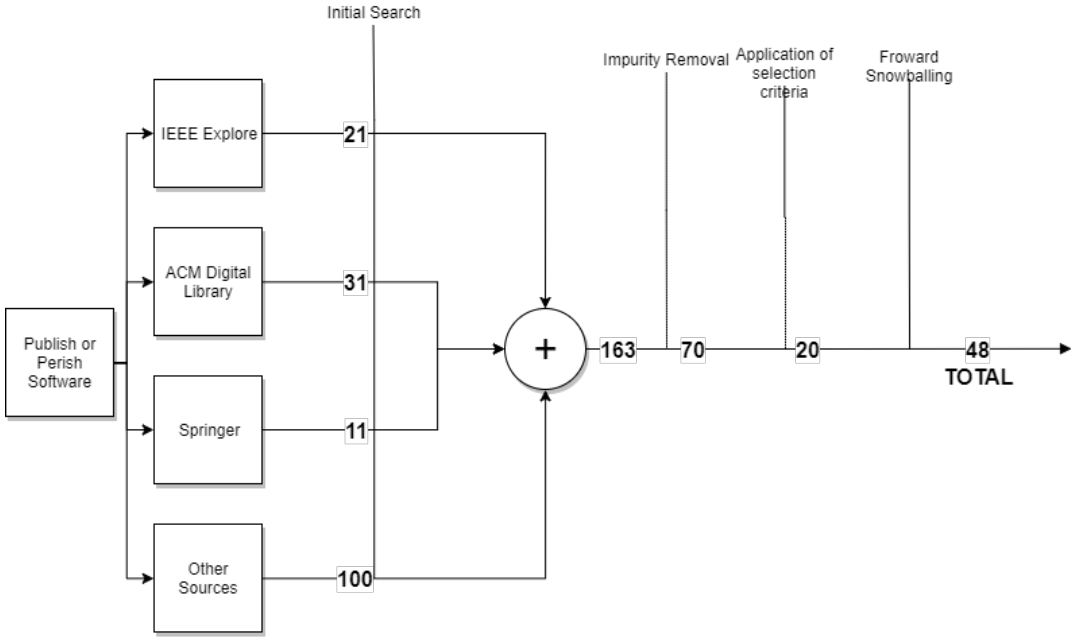

Figure 1: Overview of the search and selection process

reparametrization (eg. increasing block size) without reducing security.

Furthermore, security and user privacy was also a big concern, discussed in almost half of the researched papers. Several papers revealed the possibility of tracing blockchain transactions back to their original users, and demonstrated the possibility of certain attacks, especially on public distributed blockchains. Not only is security another huge concern, but it is also very heavily tied to scalability. As we will discuss further on, there often exists a trade off between scalability and security. The issue of *double spending* is also often brought up, saying that while the possibility of a double spending attack were currently very low, the fact that Proof-of-Work makes it possible forces blockchains to limit block time and block size.

Finally, choosing a consensus protocol, which is to say the manner in which peers may achieve consensus on the authenticity and integrity of the blockchain, can be very complicated. While bitcoin's consensus protocol, a version of Proof-of-Work, solved the problems previously associated with distrusted monetary systems, it has its limits. Novel takes on Proof-of-Work often came up in research papers, as well as other consensus protocols which aren't as dependent of computing power.

Based on these results, the following results will be divided between these 3 topics: scalability, security, and the consensus protocol.

5 ON THE ISSUE OF SCALABILITY

One of the biggest challenges that researchers are currently trying to solve is the issue of scalability. The current hardcoded limit of 1MB in the bitcoin blockchain limits bitcoin transactions to around 3-7 transactions per second, which is considerably slower than traditional credit/debit card transactions, which have speeds of almost 2000 transactions per second [46].

Proof-of-Work, the idea that by making miners spend many CPU resources, peers may achieve consensus on the integrity and validity of data being transmitted on the blockchain goes against scalability by definition, especially in entirely decentralized systems.

Proof-of-Work is a value (proof) that is very time consuming (work) to come up with but is easily verifiable by others. In the case of bitcoin, the value that a miner must find is a *nonce*. Nonces, when concatenated to the block data and passed through a SHA256 hashing function, must generate a hash under a threshold value known as the *difficulty*. Finding the nonce is a very complicated task, but the result can be easily verified by others, as they only need to verify if the hash value is inferior to the current difficulty. In the case of bitcoin, this difficulty can be modified to the average computing power of nodes on the blockchain to keep block time constant despite the variances in node computing power over time. Since increasing node power will increase the mining difficulty, vertical scaling is practically impossible.

In a completely decentralized peer-to-peer blockchain system, such as bitcoin, every participant must keep an up-to-date copy of the blockchain. As such, the whole system is held back by the weakest nodes with the most latency, which is why difficulty must be adjusted over time. The difficulty is adjusted to keep the block time at around 10 minutes, and value deemed a reasonable trade-off between speed, stability and security.

In most distributed systems, computational issues can be resolved by adding more nodes or more powerful nodes to the system. However, this is not feasible as the difficulty will change accordingly, keeping the block time at 10 minutes despite efforts to improve overall computing power on the blockchain. As such, horizontal scaling

is also a problematic hurdle for bitcoin. That is why most new proposals for cryptocurrencies tend to avoid using the Nakamoto consensus. Bitcoins take on Proof-of-Work as a consensus protocol, preferring either other protocols such as Proof-of-Stake, Hybrid consensus and Byzantine fault-tolerant protocols or using other variations of Proof-of-Work[46].

There have been massive debates amongst the bitcoin community concerning the augmentation of the current 1mb block size limit to improve transaction speeds. However, most researchers agree that there are many limits to the actual effects of reparametrization. Given the current overlay network and desirable 10-minute average block interval, the block size should not exceed 4MB. The 10-minute average block interval is a compromise decided by the original creator of bitcoin. While a shorter block time would mean faster transactions, this would require larger bandwidth for users, and the increased number of forks could cause instability within the blockchain. Thus, a 10-minute delay was decided and to maintain that delay. The block size should not exceed 4MB. However, A 4MB block size corresponds to a throughput of at most 27 transactions/sec, which is still far from traditional payment methods[8].

Another paper on the security of blockchains concluded that decreasing the average block time to 1 minute while keeping the block size at 1mb would not impact security significantly. However, even this suggestion would only increase bitcoin's throughput to 60 transactions per second, which is still reasonably low compared to traditional monetary systems[14].

There exist solutions to improve current Proof-of-Work constraints. For example, rather than resolving conflicts by choosing the most extended fork, the GHOST (Greedy Heaviest-Observed Sub-Tree) protocol uses weighted subtrees to choose which fork to continue, providing more secure means of increasing the block frequency and the block size [45]. Bitcoin-NG is another proposal that would improve current Proof-of-Work, which uses an alternative blockchain protocol[8][18].

The most natural solution is to avoid using Proof-of-Work as a consensus protocol. There exist other consensus protocols, such as Proof-of-Stake, Proof-of-luck, and Byzantine Fault Tolerant protocols, which do not rely on miners executing intensive tasks. As such, these protocols often lend themselves more easily towards scalability, usually being limited only by network latency. Improvements to scalability and other aspects of blockchains via novel consensus protocols will be further discussed in section 6.

Most of bitcoin's scalability issues come from the fact that its current protocol is hardcoded into its system. Changing bitcoin's block size to something bigger would require a *hard fork*, essentially making previous nodes useless until being updated, as they would be incompatible with the new bitcoin block version. However, most researches agree that even if this were done, it would only barely improve bitcoin's throughput[3]. That is why most new cryptocurrency proposals steer away from Proof-of-Work [8].

As previously mentioned, in a distributed blockchain network, many nodes are mining blocks in parallel, fighting to be the first to add a new block to the blockchain's main chain. When a miner starts mining new blocks, he creates a branch of the main chain. It means that the blockchain has many branches coming from its main chain. When several chains are formed, Bitcoin nodes accept the longest chain leading by at least four blocks as the record of transactions. The reselection of the record of transactions may cause some payments to be cancelled, which, when done deliberately, is known as a double-spending attack. As such, merchants are advised to wait that their transaction is included in a mined block and that several blocks are chained on top of it. Ideally, a merchant would wait until three blocks are mined on top of their block, which would assure at 100% that the block on which the transaction is included on the main chain and thus valid. However, waiting for this can take upwards of one hour, which is not always desirable for a merchant who handles several hundred transactions per second, As such, many merchants will accept only one confirmation, meaning that their transaction has been included in a block, but is not guaranteed to be on the accepted chain [42].

These are the principals on which bitcoin was founded in order to solve the double-spending problem. However, Nakamoto fails to highlight in his original paper the possibility for attackers to *pre-mine* before launching an attack, making his analysis only approximative [42].

Pre-mining, or selfish mining, is the act of secretly mining blocks without distributing them to the system until the miner decides to. A selfish miner could mine a certain number of blocks and wait for his competitors to mine until they are only one block away from being chosen as the main chain while increasing the size of his branch, and then distributing his long chain of blocks. If the selfish miner mined enough blocks, his chain would instantly become the main chain, invalidating the other miner's chains, making them waste resources while maximizing the revenue obtained from publishing his branch. In a double-spending attack, the malicious user starts by completing a transaction with a merchant, spending a quantity 'x' of cryptocurrency. The merchant then waits for one confirmation, before sending the malicious user their goods. While this is happening, the malicious user makes another transaction with the same 'x' amount of bitcoins on another branch, which he started mining secretly off the main chain. If the malicious user can mine enough blocks to be considered the main chain before the chain on which he made the first transaction can, he then publishes his chain, invalidating his first transaction with the merchant. He has thus successfully executed a double-spending attack [2] [32].

One would hope that a failed double-spending attack would be costly, discouraging miners from performing them. However, assuming the miner has a reasonable advantage (a computational power of representing at least 33%), he can always keep mining to try to catch up to the main chain and eventually submit his chain as the main chain. With simple game theory, a miner with computational power representing upwards of 33% of the blockchain obtains overall better profit from always tempting double-spending attacks rather than adopting honest behaviour [17].

Ideally, every miner would have the same computational power, making mining a much fairer game and essentially eliminating the possibility of double-spending attacks. Originally, it was assumed that no miner had an incentive to deviate from the honest strategy if the majority of miners were honest. However, this is no longer the case. A miner with computational power of at least 33% of the total blockchain power will obtain strictly better rewards

[0]Zheng, Zibin and Xie, Shaoan and Dai, Hong-Ning and Chen, Xiangping and Wang, Huaimin. (2017). Blockchain Challenges and Opportunities: A Survey. International Journal of Web and Grid Services.

by following selfish strategies rather than mining honestly. [17] Even more dangerous, if a miner (or a group of miners) were to obtains > 50% of the total computational power of the blockchain, they could execute double-spending attacks with a success rate of 100%[42]. This has become an increasingly concerning problem as mining pools, groups who share their processing power and split their rewards, increase their number of miners and, overall, computational power. Collusion between the largest mining pools could result in the possibility of a > 50% attack [2][7][50].

While double-spending attacks are technically doable, they are next to impossible to do on public blockchains as large as bitcoin. However, the existence of this vulnerability introduces an essential trade-off between scalability and security. For example, increasing the block size will increase latency and block propagation time. By increasing block propagation time, architects should increase the window of opportunity for a malicious user to execute a double-spending attack, while at the same time discouraging honest miners with sparse networks, decreasing overall security of the blockchain [51].

The primary factor enabling double-spending attacks is that every miner contributes to the consensus determination in a public blockchain. Selfish miners who execute double-spending attacks are also the miners who accept their chain as being the main chain. While this is a fundamental property of public blockchains, it makes scalability an issue without compromising security. One way of countering this is by adjusting the level of centralization of the blockchain. In a consortium blockchain, rather than all miners participating in the consensus determination, the consensus is reserved to a selected set of nodes. Depending on the consensus protocol used, this selection may be static or dynamic. Bitcoin-NG is a novel blockchain protocol which uses a random leader selection process. Spectre is another protocol that tries to eliminate the trade-off between scalability and security. As such, moving away from the Nakamoto protocol is the current solution in mitigating double-spending attacks while at the same time, eliminating the trade-off, as mentioned earlier.

While somewhat impossible with cryptocurrencies and their desired principles, the use of a completely centralized blockchain could be interesting for outside cryptocurrencies on private networks. By centralizing the consensus determination efficiency increases. If the central node it to be assumed, to be honest, we can be assured that consensus will be done in a way that favours honest behaviour. However, it becomes harder to detect if blocks have been tampered with or not. As such, private centralized blockchains should be considered in scenarios where tampered data has less of an impact: the Internet of Things is often brought up as a favourable scenario for private blockchains [7].

6 CHOOSING A CONSENSUS PROTOCOL

The majority of research on the scalability and security issues of blockchains all agree that the underlying problem lies with the current Proof-of-Work consensus protocol hardcoded into bitcoin. As long as the Nakamoto protocol is not either heavily modified or outright replaced by another consensus protocol, bitcoin will always be plagued with slow transaction times. Therefore, choosing an adequate consensus protocol plays a much more significant role than the reparametrization of blockchains (bigger block size, shorter block time, etc.). Ideally, a new consensus protocol would eliminate the trade-off between scalability and security. Here we present alternatives to blockchain Nakamoto protocol.

GHOST: GHOST (Greedy Heaviest-Observed Sub-Tree) is a Proof-of-work consensus protocol with a modified policy in the selection of the main chain created in order to mitigate the double-spending risk. Rather than choosing the chain with the most extended amount of blocks, GHOST will instead evaluate the whole chain, choosing the chain with the move work having been done onto it. In order to accomplish this, GHOST uses a DAG (Directed Acyclic Graph) rather than merely using a linked list to maintain it is blockchain. It can thus evaluate the whole chain, choosing the chain on which the most work has been done. This can eliminate selfish mining situations that are possible with the Nakamoto consensus. While the GHOST protocol succeeds in increasing the difficulty of double-spending attacks, the author notes that GHOST does not eliminate the threat [41].

Byzantine Fault-Tolerant Protocol (BFTP): The reasoning behind Proof-of-Work is that we can never assume a miner. Providing the proof-of-work is a way for miners to show that they are indeed honest miners. This problem exists because distributed blockchains are subject to what does know as the Byzantine problem and must achieve consensus despite that. However, researchers have been able to create Byzantine fault-tolerant protocols that are robust to arbitrary types of failures in distributed algorithms. *Algorand* is a cryptocurrency using such an algorithm capable of confirming transactions with latency on the order of a minute while scaling to many users. With it is consensus protocol, Algorand ensures that users never have divergent views of confirmed transactions, even if some of the users are malicious, and the network is temporarily partitioned [15].

Proof-Of-Luck: Proof-of-Luck uses a TEE (Trusted Execution Environment) platform's random number generator to choose a consensus leader, which offers low-latency transaction validation, deterministic confirmation time, negligible energy consumption, and equitably distributed mining. Proof-of-Luck is an example of a consortium blockchain, where leaders that execute the consensus determination are chosen by protocol. In the case of Proof-of-Luck, a TEE such as an Intel SGX-enabled CPU is mandated with randomly assigning leaders to achieve consensus. By removing the obligation for nodes to execute intense work, Proof-of-luck enables underpowered consumer-grade hardware to participate in mining on the blockchain, and by distributing the work equally amongst miners, we can avoid selfish mining. Scaling now becomes very easy, being limited only by network latency and the number of nodes on the network [30].

7 THE FEASIBILITY OF BLOCKCHAINS IN ITS CURRENT STATE

As highlighted in the previous results, blockchains still have several security and scalability issues that limit their ability to scale indefinitely, both horizontally and vertically. We can further pinpoint performance problems with an evaluation framework, such as the one proposed by Blockbench [9]. Their case study demonstrates with the help of Blockbench that consensus protocols are the main

bottlenecks in the cryptocurrencies Hyperledger and Etherium. This problem is not unique to these protocols. The consensus protocol is the main factor in determining the scalability of future blockchains. While many researchers agree that blockchains are not yet ready for mass usage, more research with the help of Blockbench on other examples of blockchains could lead to more accurate results [32].

Using the blockchain to face data integrity threats seems to be a natural choice, but its current limitations of low throughput, high latency, and weak stability hinder the practical feasibility of any blockchain-based solutions [13]. As such, it is hard to recommend using blockchains in its current state.

However, the Internet of Things, which is to say the network of numerous connected physical objects, could be an interesting platform for blockchains despite their current drawbacks. A critical issue with connecting various objects and having them communicate to one and another is privacy. These objects spread sensitive information about their users, and when a centralized company manages such sensitive data, the leak of user's privacy becomes a real issue. That is why a distributed private-by-design IoT makes sense. While the tendency of IoT hardware to be underpowered hinders the use of Proof-of-Work, with the rise of other consensus protocols, the blockchain for the IoT could be very feasible.

8 CONCLUSION

In this Systematic Review we discussed the various challenges of architecting blockchain systems and possible future solutions to mitigate said problems. We discussed how current blockchains such as bitcoin are fundamentally limited in scalability due to their underlying protocol and the limits of mitigation through reparametrization. We discussed current blockchain security issues such as double spending attack and how novel crytocurrencies and consensus protocols were being developed to further eliminate the possibility of a double spending attack. Consensus protocols were then presented, demonstrating the various choices besides Proof-of-Work that currently exist. Finally, we briefly touched the subject of the feasibility of blockchains outside of cryptocurrencies in their current chain, deciding that while blockchains in their current state could be useful for domains such as the Internet of Things, companies should wait on the more widespread adoption of novel consensus protocols such as GHOST and BFTP.

While this paper brings out the most obvious challenges and solutions concerning blockchains, it only scratches the surface of the whole subject. A more in depth of each problem category (scalability, security and consensus protocols) would provide readers with a better comprehension of the existing challenges and the solutions available to them. Blockchains are a very new technology. Advances are being done every day. As such, it would be interesting to do this further analysis when blockchains achieve a more mature status. This could potentially provide the future paper with more solutions to the existing problems.

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