Blockchains for IoT Payments: A Survey

Conference Paper · December 2018

DOI: 10.1109/GLOCOMW.2018.8644522

Sigrid Schefer-Wenzl
FH Campus Wien

Igor Miladinovic
FH Campus Wien

Blockchains for IoT Payments: A Survey

Alice Ensor, Sigrid Schefer-Wenzl, Igor Miladinovic
Computer Science and Digital Communications
University of Applied Sciences Campus Vienna
Vienna, Austria
firstname.lastname@fh-campuswien.ac.at

***Abstract*—Blockchains and other Distributed Ledger Technologies (DLTs) are a much-proposed solution for an Internet of Things (IoT) payment platform. Because of their decentralized networks, they are one of the few technologies which allow for true Machine-to-Machine financial transactions, considered essential for the IoT economy. In this paper, we examine the issues surrounding IoT payment systems, including their requirements and proposed specifications. We will also discuss limitations of blockchains to meet these specific requirements, and whether other DLTs or possible optimization solutions for blockchains can overcome these limitations. We present example IoT payment implementations using DLTs to illustrate the opportunities surrounding this technology. This paper aims to capture the breadth and depth of this topic to understand why IoT payment systems are essential to the IoT economy and how blockchains might provide the answer for implementing them in an effective manner.**

***Index Terms*—Blockchain, Internet of Things, Distributed Ledgers, Machine-to-Machine, Sensing-as-a-Service, Payment**

I. Introduction

The Internet of Things (IoT) represents an environment filled with a varied entourage of electronic devices which all use various networking protocols and applications to stay interconnected through the internet. It is sometimes used along with the term Internet of Everything which encompasses the interactions between people, devices, and data, promising a world where devices can communicate directly with one another and exchange a wide variety of information [1]. However, the IoT economy needs a way for sensors and devices to make monetary transactions in exchange for services without the necessity of a third party (e.g. Machine-to-Machine (M2M), Peer-to-Peer (P2P)) [2]. Additionally, with the advent of 5G, these transactions and exchanges will occur primarily over an internet-based network, something that any billing or payment system will have to take into consideration. Blockchain, on the other hand, is an emergent Distributed Ledger Technology (DLT) that is decentralized and allows for secure, anonymous, and immutable transactions [3]. In this work, we contend that these characteristics make blockchains an ideal solution for IoT payments, although there are still multiple challenges to be overcome.

One primary issue of contention with IoT environments is how the business side of IoT should work. This lack of clarity has hindered the growth of IoT to some extent, and the platforms and protocols used in the exchange of monetary rewards for services ought to be defined more clearly. IoT services themselves can include selling sensor data, as seen in the Sensing-as-a-Service model [4], or electrical charges from a charging station to an electrical autonomous vehicle [5]. For both kinds of services, automatic micropayments in a pay-per-use model would be most beneficiary [6]. As mentioned in [2], traditional E-business models have relied on a trusted third party, such as a bank, to act as an intermediary during transactions. This has limited IoTs ability to take advantage of M2M, P2P, and even Machine-2-Peer (M2P) transactions. To be effective for IoT, business processes must be adapted so that they, like physical objects and people, are able to integrate into IoT's information network. One possible way to do this are blockchain technologies because, due to their distributed nature, they allow true P2P transactions without third party intervention [2].

Blockchains also help with other issues caused by third parties in IoT financial transactions, namely the lack of anonymity for the users and additional security risks. Users simply do not want hundreds of devices storing their transaction history, particularly if it's in any way connected to their bank account [6]. This can be particularly uncomfortable when one considers the recent data collecting and surveillance scandals. As we will see in this work, one of the advantages of blockchains is the user's ability to maintain a certain amount of anonymity. Furthermore, the use of third party institutions leads to increased transaction fees, which in the case of micropayments is also unwanted. Very few people want to complete a transaction where the transaction fee is higher than the amount that is being transferred [7]. Admittedly, transaction fees can also be an issue for blockchain technologies, but there are multiple proposals to improve these.

In our previous work we proposed a layered IoT architecture for smart cities [8], [9]. The architecture is based on a common infrastructure of sensors and actuators which can be used by multiple smart city applications. Until now we have focused on the scalability and performance of this architecture, in this paper we elaborate on solutions for payment. To handle the demands of such an environment, we are currently working on a smart payment system that utilizes web based and cloud computing services. For this system, a payment platform is required that supports micropayments with little or no transaction fees and extremely quick transaction times. This platform must allow users end-to-end control over transactions, as well as a certain amount of mobility and anonymity. In addition, it is also important that this platform is capable of Machine-to-Machine (M2M) transactions. This payment platform should also be accessible, scalable, decentralized and secure—the requirements which are supposed to be addressed by blockchain technology.

This paper aims to examine the compatibility of blockchains with IoT technologies, specifically focusing on IoT payment transactions. We shall discuss which characteristics make blockchains an ideal solution for M2M and P2P transactions between IoT devices and participants. Additionally, we present several issues blockchains have in achieving fast and cheap transactions, as well as possible improvements.

The remainder of this paper is structured as follows: in Section II, we present the concepts behind Bitcoin and Ethereum. Section III discusses the advantages and disadvantages of blockchains specifically for IoT payments. Subsequently, Section IV highlights ways to optimize blockchains so that they may be better suited for IoT payment implementations. In Section V, we review selected implementations of blockchains as IoT payment services. Finally, Section VI concludes the paper.

II. Blockchain Concepts

In this section we review some of the essential concepts behind blockchains by examining two of the best known blockchain platforms: Bitcoin and Ethereum. This is done to achieve a basic understanding of blockchains before discussing their use as an IoT payment solution in Section III.

Although it is based on several older underlying technologies, the first DLT that could be truly considered a blockchain was Bitcoin [10]. Bitcoin's creator, Satoshi Nakamoto, envisioned a cryptocurrency that removed trusted 3^{rd} parties such as banks for financial transactions and instead implemented a cryptographic Proof-of-Work (PoW) to ensure that the transaction is fair to both buyers and sellers. This would allow the blockchain to be distributed across a large network instead of being centralized in several locations. Furthermore, these transactions would be immutable, because Nakamoto believed that reversible transactions degraded merchants' trust in their customers, forcing them to calculate a certain amount of fraud while conducting business, thus raising prices overall [10].

Bitcoin, as well as many other blockchain technologies, store records detailing transaction histories and other data in blocks which are arranged on continuously growing chains often arranged in Hash trees (e.g. Merkel Tree) [10], [11]. Often miners are given the responsibility of maintaining the ledger by verifying and adding new blocks. They do this by encrypting the block with a PoW which is defined differently by the various blockchain technologies. Bitcoin miners, for example, create PoWs by repeatedly performing a double-SHA256 hash of the previous blocks hash until it is less than a pre-defined difficulty target. This process consumes an incredible amount of both time and energy because it is a trial and error process. Additionally, as the target is re-calibrated every 2016 blocks, the process becomes increasingly complex [11].

Perhaps second only to Bitcoin, Ethereum is a DLT platform which allows anyone to develop smart contract applications, store data, and exchange Ether, Ethereum's currency. Thanks to adjustments to the PoW and Hash Tree, Ethereum has improved transaction times and scalability capabilities in comparison to Bitcoin [11]. Further algorithms are in place to prevent unnecessary inflation and overcharging of transaction fees. Ethereum is particulary relevant as multiple other cryptocurrencies are built upon its platform.

III. Blockchains as IoT Payment Solutions and their Limitations

As already mentioned in Section I, blockchains offer many attractive solutions for IoT environments. This section evalutes the many advantages, as well as disadvantages, blockchain technologies have as a payment platform for IoT implementations.

As previously mentioned, some of the key concepts behind blockchains are that they are distributed, immutable, and secure. It is these three chracteristics which make the technology ideal for IoT payments. Because they are distributed, they allow IoT devices to have direct M2M transactions because there is no need for a trusted third party. The immutability of these transactions is ensured by the PoWs which protect the blocks, making the transaction history impossible to reverse [10]. Furthermore, these transactions are secure, in part because of the PoWs, but also because most blockchains have algorithms in place to ensure false blocks are left unconfirmed and are rejected by the network [11], [12].

Many blockchains are also capable of micropayments, which is seen as essential for IoT. This is because in the IoT economy, devices constantly request services, often in the form of data, from other devices. In exchange for these services, the device will require some form of payment: a payment that is both small, metered, and should be anonymous [6]. Anonymity is also an area where blockchains excel when compared to traditional banks and credit cards, especially in regards to IoT. This is because users would probably be uncomfortable with having their credit card information stored by hundreds of IoT devices.

One major obstacle for Blockchains in IoT implementations is the transaction fees. These fees were created by the need to reward miners for their efforts, but unfortunately, because many cryptocurrencies allow these fees to be market-based, they can become quite expensive. For example, on December 21, 2017, Bitcoin's transaction fees soared to an average of 54 US dollars [13], causing many online marketplaces to stop accepting the currency [14]. As of May 2018, Bitcoins transaction fee has been hovering around 1 US dollar, but this is still not attractive for IoT transactions which may range in the micro-cents. On the other hand, Ethereum has mechanisms to control transaction fee inflation [11]. Even so, its transaction fee has also suffered from fluctuations, reaching a high of 4 US Dollars in early 2018 [15].

Another one of the most problematic issues for many blockchains is the transaction time. Bitcoin, which has a fixed time of ten minutes for creating new blocks, supports about 7 transactions-per-second (tps) and has been proven to perform poorly in times of high traffic [16]. Ethereum, on the other hand, has a theoretical transaction time of 12 seconds. However, this transaction time is also largely dependent on the networks congestion levels [17]. Both situations can be problematic in an IoT payment system where many micro-transactions need to be completed within seconds.

Related to the issue of transaction times is network scalability. Because each ledger modification is broadcast to the global Bitcoin blockchain, the network becomes unnecessarily clogged with broadcast messages and overwhelmed at times of high traffic [16]. Network performance degrades as the number of transactions increases [18]. Additionally, by comparing the transaction rate of Bitcoin (7 tps) to Visa, which has around 60,000 tps, it is clear that Bitcoin has a serious problem [18]. Furthermore, one study found that in mid-March 2018, the Bitcoin network performed approximately 26 quintillion hashes per second while only being able to maintain an average of 2-3 tps. This left the network with a hash to completed transaction ratio of about 8.7 quintillion to 1 [19]. This study also estimated Bitcoin has an estimated energy usage of 300kWh per transaction [19], which is about the average household electrical consumption per month [20]. Of course, this number is a bit misleading because it takes the same amount of energy to mine an empty block, but the energy usage of Bitcoin is a cause for concern. Ethereum and other blockchain platforms usually do not have scalability problems as drastic as the ones which plague Bitcoin [11], but their performance is still largely determined by network congestion because each new transaction must be broadcast to the entire global blockchain [3].

IV. Improving Blockchains for IoT Payments

After reading about the multiple disadvantages of blockchains in IoT environments, it is possible to become disenchanted with the technology as an IoT business solution. Fortunately, there are multiple proposals about how to improve this technology to make it faster, cheaper, more scalable, and more IoT friendly. This section examines some of these technologies capable of optimizing blockchains for IoT payments, including the Lightning Network for Bitcoin and virtualized DLTs (vDLTs). It also introduces an alternative DLT technology: Directed Acyclic Graphs (DAGs).

One possible solution for decreasing transaction times, lowering fees, and improving scalability is the use of Directed Acyclic Graphs (DAGs). The DAGs are a newer type of DLT, and like blockchains, it links blocks or nodes together with some form of consensus. However, unlike blockchain, these nodes are not arranged linearly in chains but rather in directed graphs which allows them to cross-verify one another. Consensus in DAG networks are usually reached based on the network's state, and in most examples, a user must first confirm a given number of previous transactions before they can create a new one [18]. This eliminates the need for both miners and the energy heavy hardware that is required to create the ever more-complex Hash based PoWs while also improving the scalability of the network. [17].

Some examples of DAG based cryptocurrencies include IOTA which is specifically designed with IoT in mind [7], and Nano, which is a hybrid between DAG and Blockchain technologies [21]. DAGs are a relatively new form of DLT technologies, so it remains to be seen if they can maintain the level of security and decentralization of the more mature blockchain technologies. In addition to being relatively untested, there is a reluctance among cryptocurrency aficionados in accepting DAGs because they do not rely on highly encrypted, hash protected PoWs. While DAG proponents claim this is a positive as it makes them safe from the impending threat of the quantum computers [7], this argument has done little to win over the tried and true Bitcoin and Ethereum enthusiasts. Considering this concern, is there any way to make Bitcoin and Ethereum faster, cheaper, and more scalable for use in IoT implementations?

Poon and Dryja suggest that even Bitcoin can support an unlimited number of transactions per second with extremely low fees [16]. They do this by sending sequential micropayments between two end users over what they call a network of micropayment channels. It is important to remember that the micropayment channels are real bitcoin transactions which simply defer broadcasting the transaction information until the channel between the two parties are closed.

The Lightning Network works by building a bidirectional micropayment channel between two parties which allows an unlimited amount of micropayment transactions [16]. These transactions can include refunds and cancellations. Each of these transactions are protected with a timestamp and a hashlock to prevent theft, and once the payment relationship is done, the channel is closed, and the end result is broadcast to the global blockchain. By rerouting the transaction information over microchannels and using time locks, they ensure that the global Bitcoin blockchain is not overwhelmed by the multitude of microtransactions [16]. Proponents of the Lightning Network claim that the knowledge of the transaction is only necessary between the two parties, so why clog up the rest of the blockchain with unnecessary information when it is possible to defer broadcasting the transaction data until the transaction is complete.

One of the drawbacks of the Lightning Network is that it solves only Bitcoin's scalability issues, not those of other blockchains. The same is true for another Bitcoin soft fork change, SegWit [22] while the Raiden Network [23] and Plasma [24] offer solutions like that of the Lightning Network, but for Ethereum instead. There is, however, one related solution that claims it can solve both the scalability issues of any blockchain technology and improve blockchain interoperability. This solution is virtualized DLTs [3].

As discussed above, many public blockchains, including Bitcoin, Ethereum, and Ripple [25], have issues because each block that is fully participating must process every transaction broadcast to the global blockchain [3]. This prevents the blockchains from handling a large amount of transactions and keeps the network traffic unnecessarily high. To solve this, it might be possible to draw inspiration from Network

Function Virtualization (NFV) [26], [27] and create a layer of virtualized DLT functions, which are merely abstractions of DLT technologies. An architecture proposed by [3] creates this abstraction with a virtualization layer which is based on the virtual machine monitor, hypervisor. This layer is responsible for decoupling the virtual resources from their physical ones via virtual machines. These resources are connected, hosted, and routed by a virtual network that is composed of virtual nodes and links [3]. A RESTful API [28] is used to support the deployment of vDLT services.

Considering the increased popularity and effectiveness of network solutions based on NFV, virtualizing blockchains and other DLT technologies might be key to increasing the technology's scalability and speed. Additionally, as already mentioned, vDLTs have the benefit of supporting interoperability between DLT technologies. This means users would not be restricted by what cryptocurrency is used by their transaction partner. With the virtual layer overlay provided by hypervisor, the parties can complete transactions from Bitcoin to IOTA or from IOTA to Ripple [3].

A similar solution which also helps to deal with the scalability and interoperability issues is Interledger. Instead of using virtual machines, it aims to make blockchains more internet-like by using internet protocols as an overlay for blockchain and other currency platforms [29]. It results in similar gains in scalability and speed as the vDLTs, while promoting interoperability. Interledger is still in its developmental stages but currently open for use in small implementations.

V. Existing DLT Solutions for IoT Payment Systems

This section provides a review of IoT payment and billing systems which use DLT platforms, including both blockchain or DAG, as a basis. The idea of paying for IoT services with blockchain technologies is much discussed in literature concerning smart cities, smart homes, and even smart parking systems [30], [31], but very few works try to explicate the architectural groundwork for these systems, let alone try to implement them in any practical form. In the following subsections, we shall discuss some of these relevant examples.

A. IoT Electric Business Model

In [2], Zhang and Wen explain that traditional E-business models are not suitable for IoT because of their reliance on third-party intermediaries which prevent P2P/M2M payments. IoT's ability to provide P2P/M2M interactions is largely seen as one of its primary advantages, so it would make sense to have payment systems that also take advantage of these relationships. Because blockchains work without the third-party intermediary, the authors propose an IoT E-business model that is built on Bitcoin's protocol [2].

This IoT E-business model is quite different from traditional ones because it no longer focuses on customer relationships and product innovation. Instead the model proposed in [2] consists of four modules: the entity, operation mode, transaction mode, and commodity modules. Entities can be seen as commodity providers or consumers interested in finding and purchasing IoT products, such as sensor data [2]. These IoT products can include smart properties, such as cars, houses, or even parking places. Operation mode provides the guidelines of the E-business process, and is where the smart contract is signed, timestamped, and used to record the transaction details. And lastly, the transaction mode is responsible for handling the blockchain platforms. Here the authors create a special cryptocurrency that is specific to IoT, IoTcoin, which acts as a P2P transaction mechanism until the final payment can be payed-out in Bitcoin [2].

B. Blockchain for Sensing-as-a-Service

Sensing-as-a-Service is a much-discussed business model pattern for IoT. The idea is to offer data from devices with sensing capabilities as a service in return for monetary rewards [4]. For example, a car manufacturer might be willing to pay a vehicle owner for data generated by the vehicle as it drives around the city. However, there are multiple challenges that are presented by such a system: the data values need to be secured and safe from manipulation; sensors and owners need to authenticated; and finally, the sensor owner needs to be financially rewarded for the data provided [32]. In [32], the authors propose Bitcoin as a possible solution for all the above challenges.

To demonstrate how Bitcoin might be used as a Sensing-as-a-Service platform, the authors give an example of a personal connected weather station that is equipped with multiple sensors for measuring things like temperature, wind speed, and air pressure [32]. In addition to the benefits this weather data may provide to the weather station owner, it could be of further use to the owner's neighbor, meteorologists, researchers and even personal fitness platforms. Of course, this all depends on the willingness of the owner to share the data, a willingness that might be increased if there were some financial incentives to do so [32].

So how do we get cash flowing in this scenario? To achieve this, the authors introduce an atomic process which uses the Bitcoin protocol to allow for the exchange of data and money between two machines. For example, a machine might request data concerning air humidity from a sensor on our personal weather station. The requesting machine and the sensor are then able to exchange money and data over a blockchain network. Security of this transaction is ensured because they share a key pair which ensures unique identification of both devices [32]. The authors also discuss various facets of Bitcoin in terms of scalability, anonymity, and cryptographic viability. One interesting aspect is that the authors assume the Bitcoin's fees would become more affordable as the network becomes more exposed to supply and demand market dynamics. Considering that this paper was written in 2014, the opposite has proven to be true.

A similar implementation that uses the Sensing-as-a-Service principle is presented in [33]. This implementation consists of a requester client, a sensor client, a sensor, repository, and the Bitcoin network. The requester client can request data from the sensor repository for all registered sensors. It is also able to send Bitcoins to the sensor's Bitcoin address. The sensor client, on the other hand, needs to be able to recognize when it has received Bitcoins in exchange for information and be able to publish the requested data. It is implemented with a websocket client which registers itself to the Sensor Repository via a websocket API. And finally the Sensor Repository is basically a database of registered sensors that uses a web front end and a RESTful HTTP API to search or register a sensor [33]. This implementation was only a prototype but clearly demonstrated the possibility of M2M transactions using Bitcoin.

C. Shared Things

With the project Shared Things, a team from the University of Sussex evaluates the advantages of blockchains for micropayments in IoT shared economy applications [34]. Some of the application modules they explore include SmartBasket, AutoPay, and Rewards Gateway, all of which use the design-prototype platform to automate certain tasks by interacting with real-world objects, such as a user's car. For example, AutoPay provides drivers with an in-car payment service over their vehicle's display. This payment service utilized blockchain technology to allow peer-to-peer transactions and to immutably store Autopay's history [34]. Shared Things presents many interesting scenarios which could utilize the benefits of blockchain technologies but it is unclear if these modules were ever actually implemented after the project's conclusion.

D. M2M Billing

Another M2M billing service is implemented by a team from Innopolis University in Russia, specifically for Electric Autonomous Vehicles. They envision a system which uses DLTs and IOTAs Tangle network to allow M2M monetary transactions between the vehicle and a charging station in exchange for electricity [5]. The project's authors would eventually like to extend the concept to electric roads which allow for charging on-the-go. In this scenario, the payment framework based on IOTA would act as a meter which exchanges IOTAs for kWh.

The project's billing platform architecture consists of three layers: the physical, network and service layers. The physical layer consists of the hardware components used for gathering data about the charging process and for communication [5]. These include the kWh Meter used to measure the electricity consumed, Electric Vehicle Supply Equipment Controller which ensures the electricity is used efficiently, and the Main Controller which communicates with the higher layers via Message Queuing Telemetry Transport (MQTT). The network layer is responsible for M2M communication and handling the DLT. This layer uses the IOTA tangle to both store relevant data and handle monetary transactions [5]. Furthermore, it uses MQTT for inter-device communication and a Flash Channel, a bidirectional off-tangle payment channel, to allow for secure real-time streaming of transactions. Finally, the service layer uses the two layers below to offer services for both the service providers and the consumers. This includes charging services for the vehicles and data for the service providers.

To further demonstrate the validity of their billing platform, the Innopolis team developed a proof-of-concept implementation with a Raspberry Pi and a temperature sensor [35]. This implementation is supposed to work similar to the electric road and charging station scenarios described above, but here the temperature readings are seen as a service to which the Raspberry Pi subscribes. With each reading, the client is billed, and the balances of both parties saved to the tangle. A user interface shows the temperatures recorded and how many IOTAs remain in the user's and the Raspberry Pi's balance [35].

What makes this M2M billing system interesting is that it has a working proof-of-concept that demonstrates that DLT technologies such as DAGs and Blockchains can both handle metered M2M transactions as well as store relevant data for the transactions (e.g. the temperature readings). It is an easy-to-understand and replicable example and architecture which can be applied to all manner of IoT applications.

VI. Conclusion

To expand economically, IoT needs a financial platform which complements its own elements of decentralization and support for M2M/P2P/P2M communication. It also needs a platform that is anonymous, secure, immutable, and which allows for fast microtransactions for little or no transaction fees. This paper has examined some of the elements required for an IoT business model to work. It has also evaluated blockchain technologies, examining their advantages, disadvantages, and optimization possibilities for IoT implementation. The implementations reviewed in this paper demonstrated that the use of DLTs for IoT monetary transactions is possible and even advantageous. Although blockchains and DLT technologies may require further optimization to be truly effective as an IoT payment platform, they promise many exciting uses within the world of IoT.

References

[1] M. H. Miraz, M. Ali, P. S. Excell, and R. Picking, "A Review on Internet of Things (loT), Internet of Everything (IoE) and Internet of Nano Things (IoNT)," in *Proc. IEEE 2015 Internet Technologies and Applications (ITA2015)*, Wrexham, UK, Sep. 2015, pp. 219–224.

[2] Y. Zhang and J. Wen, "The IoT Electric Business Model: Using Blockchain Technology for the Internet of Things," *Peer-to-Peer Networking and Applications*, vol. 10, no. 4, pp. 983–994, Jul. 2017. [Online]. Available: https://doi.org/10.1007/s12083-016-0456-1

[3] F. R. Zu, J. Liu, Y. He, P. Si, and Y. Zhang, "Virtualization for Distributed Ledger Technology," *IEEE Access*, vol. 6, pp. 25 019–25 028, Apr. 2018.

[4] W. Sheng, J. Tang, X. Xiao, and G. Xue, "Sensing as a Service: Challenges, Solutions and Future Directions," *IEEE Sensors Journal*, vol. 13, no. 10, pp. 3733–3741, Oct. 2013.

[5] D. Strugar, R. Hussain, M. Mazzara, and V. Rivera, "M2M Billing for Electric Autonomous Vehicles," University of Innopolis, Apr. 2018. [Online]. Available: https://arxiv.org/abs/1804.00658

[6] J. Rykowski and W. Cellary, "Anonymous Pico-Payments for Internet of Things," in *Enriching Urban Spaces with Ambient Computing, the Internet of Things, and Smart City Design*, S. Konomi and G. Roussos, Eds. Hershey, Pennsylvania: IGI Global, Oct. 2016, pp. 114–126.

[7] S. Popov, “The Tangle,” IOTA, Oct. 2017. [Online]. Available: https://iota.org

[8] I. Miladinovic and S. Schefer-Wenzl, “Urban Mobility in the City of Things,” in *International Conference on Working Class Districts*, Vienna, Austria, September 2017.

[9] I. Miladinovic and S. Schefer-Wenzl, “Dymanic Allocation of Smart City Applications,” *Open Journal of Internet Of Things (OJIOT)*, Accepted, special Issue: Proceedings of the International Workshop on Very Large Internet of Things (VLIoT 2018) in conjunction with the VLDB 2018 Conference in Rio de Janeiro, Brazil.

[10] S. Nakamoto, “Bitcoin: A Peer-to-Peer Electronic Cash System,” Bitcoin, Oct. 2008. [Online]. Available: https://bitcoin.org/en/bitcoin-paper

[11] V. K. Chaugule, “A Next-Generation Smart Contract and Decentralized Application Platform,” Ethereum. [Online]. Available: https://github.com/ethereum/wiki/wiki/White-Paper

[12] J. Chen, “Flowchain: A Distributed Ledger Designed for Peer-to-Peer IoT Networks and Real-time Data Transactions,” Flowchain Open Source Project, Devify Inc, Jan. 2017. [Online]. Available: https://flowchain.co/publication.html

[13] “Bitcoin Avg. Transaction Fee Historical Chart,” BitInfoCharts, May 2018. [Online]. Available: https://bitinfocharts.com/comparison/bitcoin-transactionfees.html

[14] T. Lee, “Bitcoin’s Transaction Fee Crisis is Over - For Now,” Arstechnica, Feb. 2018. [Online]. Available: https://arstechnica.com/tech-policy/2018/02/bitcoins-transaction-fee-crisis-is-over-for-now/

[15] “Ethereum Avg. Transaction Fee Historical Chart,” BitInfoCharts, June 2018. [Online]. Available: https://bitinfocharts.com/comparison/ethereum-transactionfees.html

[16] J. Poon and T. Dryja, “The Bitcoin Lightning Network: Scalable Off-Chain Instant Payment,” The Lightning Network, Jan. 2016. [Online]. Available: http://lightning.network/docs

[17] R. Beck, J. S. Czepluch, N. Lollike, and S. Malone, “Blockchain The Gateway to Trustfree Cryptographic Transactions,” in *Twenty-Fourth European Conference on Information Systems(ECIS,2016)*, Istanbul, Turkey, Jun. 2016.

[18] M. Bottone, F. Raimondi, and G. Primiero, “Multi-agent Based Simulations of Block-free Distributed Ledgers,” in *The 32nd IEEE International Conference on Advanced Information Networking and Applications(AINA2015)*, Krakow, Poland, May 2018, (Accepted/In press).

[19] A. de Vries, “Bitcoin’s Growing Energy Problem,” *Joule*, vol. 2, no. 5, pp. 801–805, May 2018.

[20] “Electric Power Consumption (kWh per capita),” The World Bank, 2014. [Online]. Available: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[21] C. LeMahieu, “RaiBlocks: A Feeless Distributed Cryptocurrency Network,” Nano, Dec. 2017. [Online]. Available: https://nano.org/en/about/

[22] “Segwit.” [Online]. Available: https://segwit.org/

[23] “Raiden.” [Online]. Available: https://raiden.network/

[24] “Plasma.” [Online]. Available: http://plasma.io/

[25] D. Schwartz, N. Youngs, and A. Britto, “The Ripple Protocol Consensus Algorithm,” Ripple Labs Inc, 2014. [Online]. Available: https://ripple.com/

[26] J. Costa-Requena, J. L. Santos, V. F. Guasch, K. Ahokas, G. Premsankar, S. Luukkainen, O. L. Prez, M. U. Itzazelaia, I. Ahmad, M. Liyanage, M. Ylianttila, and E. M. de Oca, “SDN and NFV integration in generalized mobile network architecture,” in *2015 European Conference on Networks and Communications (EuCNC)*, June 2015, pp. 154–158.

[27] J. Li, E. Altman, and C. Touati, “A General SDN-based IoT Framework with NVF Implementation,” *ZTE Communications*, vol. 13, no. 3, pp. 42–45, Sep. 2015. [Online]. Available: https://hal.inria.fr/hal-01197042

[28] R. T. Fielding, “REST: architectural styles and the design of network-based software architectures,” Doctoral dissertation, University of California, Irvine, 2000. [Online]. Available: http://www.ics.uci.edu/ fielding/pubs/dissertation/top.htm

[29] S. Thomas and E. Schwartz, “The Protocol for Interledger Payments,” Interledger, 2016. [Online]. Available: https://interledger.org/interledger.pdf

[30] “Technological Areas 2017,” Smart Mobility World, 2017. [Online]. Available: http://www.smartmobilityworld.net/en/aree-tecnologiche-2017

[31] J. Sun, J. Yan, and K. Z. K. Zhang, “Blockchain-based Sharing Services: What Blockchain Technology can Contribute to Smart Cities,” *Financial Innovation*, vol. 2, 2016. [Online]. Available: https://doi.org/10.1186/s40854-016-0040-y

[32] K. Noven, D. Volland, D. Wörner, and E. Fleisch, “When Money Learns to Fly: Towards Sensing as a Service Applications Using Bitcoin,” 2014. [Online]. Available: https://arxiv.org/abs/1409.5841

[33] D. Wörner and T. von Bomhard, “When Your Sensor earns Money: Exchanging Data for Cash with Bitcoin ,” in *Proc. ACM International Joint Conference on Pervasive and Ubiquitous Computing (ACM2014)*, Seattle, Washington, Sep. 2014, pp. 295–298.

[34] S. Huckle, R. Bhattacharya, M. White, and N. Beloff, “Internet of Things, Blockchain and Shared Economy Applications,” *Procedia Computer Science*, vol. 98, pp. 461–466, 2016.

[35] D. Strugar, R. Hussain, M. Mazzara, V. Rivera, J. Lee, and R. Mustafin, “On M2M Micropayments: A Case Study of Electric Autonomous Vehicles,” University of Innopolis, Apr. 2018. [Online]. Available: https://arxiv.org/abs/1804.08964