# The Performance Evaluation of Blockchain-based Security and Privacy Systems for the Internet of Things: A Tutorial

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*Abstract*—This paper presents research challenges and a tutorial on performance evaluation of blockchain-based security and privacy systems for the internet of things (IoT). We start by summarizing the existing surveys that deal with blockchain security for IoT networks. Then, we review the blockchain-based security and privacy systems for seventeen types of IoT applications, e.g., Industry 4.0, Software Defined Networking, Edge computing, Internet of Drones, Internet of Cloud, Internet of Energy, Internet of Vehicles, etc. We also review various consensus algorithms and provide a comparison with respect to the nine properties such as latency, throughput, computation, storage, and communication costs, scalability, attack model, advantage, and disadvantage...etc. Moreover, we present the security analysis techniques and provide a classification into four categories, including, BAN logic, game theory, theory analysis, and AVISPA tool. In addition, we analyze the performance metrics, blockchain testbeds, and cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks. Based on the current survey, we discuss the major steps to follow for building and evaluating blockchain-based security and privacy systems. Finally, we discuss and highlight open challenges and future research opportunities.

*Index Terms*—Security, Privacy, Blockchain, IoT, Testbeds, Experimentation environments.

## I. INTRODUCTION

Today, with the emergence of many low-cost and powerful devices such as sensors and RFIDs associated with various communication media, the Internet of Things (IoT) has gained tremendous popularity, which offers a high potential for the development of not only different home automation systems but also various industrial applications, such as connected drones, connected health, smart farming, wearables, among other areas. The IoT market is projected to increase from over 15 billion devices in 2015 to more than 75 billion in 2025. This projection indicates that on average, there will be at least 25 personal IoT devices for every person on earth [1]. The large-scale and transverse nature of IoT systems, with the different elements and components associated with the implementation of such systems, has opened new security and privacy challenges [2], [3].

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Currently, the "blockchain" is one of the most appropriate candidate technologies that can provide a secure and distributed ecosystem for IoT networks. The security characteristics that blockchain promises are unprecedented and truly inspiring [4], [5]. The concept of a blockchain-based IoT has attracted considerable research interest since decentralizing the IoT using the blockchain technology offers the following five potential advantages: a) increases fault tolerance and eliminates single points of failure; b) allows implementing secure software updates on IoT devices; c) provides accountability and traceability since IoT data stored on the blockchain are immutable; d) enhances the security by providing authentication, access control, and confidentiality; e) allows secure micro-transactions for IoT data [6]. Therefore, there are four primary types of blockchains, namely, a) public blockchain, b) consortium blockchain, c) private blockchain, and d) hybrid blockchain. The public blockchain enables any person to join as miners, developers, users, or other members of the community. Each transaction on a public blockchain is fully transparent, which means that any person can view the details of the transaction. The public blockchain is accompanied with a token, which is usually developed to incentivize and reward network participants [3]. The private blockchain is a network that requires an invitation to join the service. The transactions are private and the network is more centralized than the public blockchain. The private blockchains are especially relevant for companies that want to collaborate and share data. The consortium blockchain is a private blockchain but governed by a group rather than a single entity. The hybrid blockchain combines the charactistics of both public and private blockchains, where members can decide who can participate in the blockchain or which transactions are made public.

In the literature, there are many surveys that covered different aspects of blockchain-based security and privacy systems for the internet of things. As shown in Table I, we categorize the blockchain surveys according to the following criteria:

- *IoT application:* It states if the survey has provided a taxonomy for blockchain-based IoT applications.
- *Consensus algorithms:* It indicates whether the survey presented consensus algorithms and provided a comparative analysis.
- *Security analysis techniques:* It states if the survey has provided the security analysis techniques used in the performance evaluation of blockchain-based security and
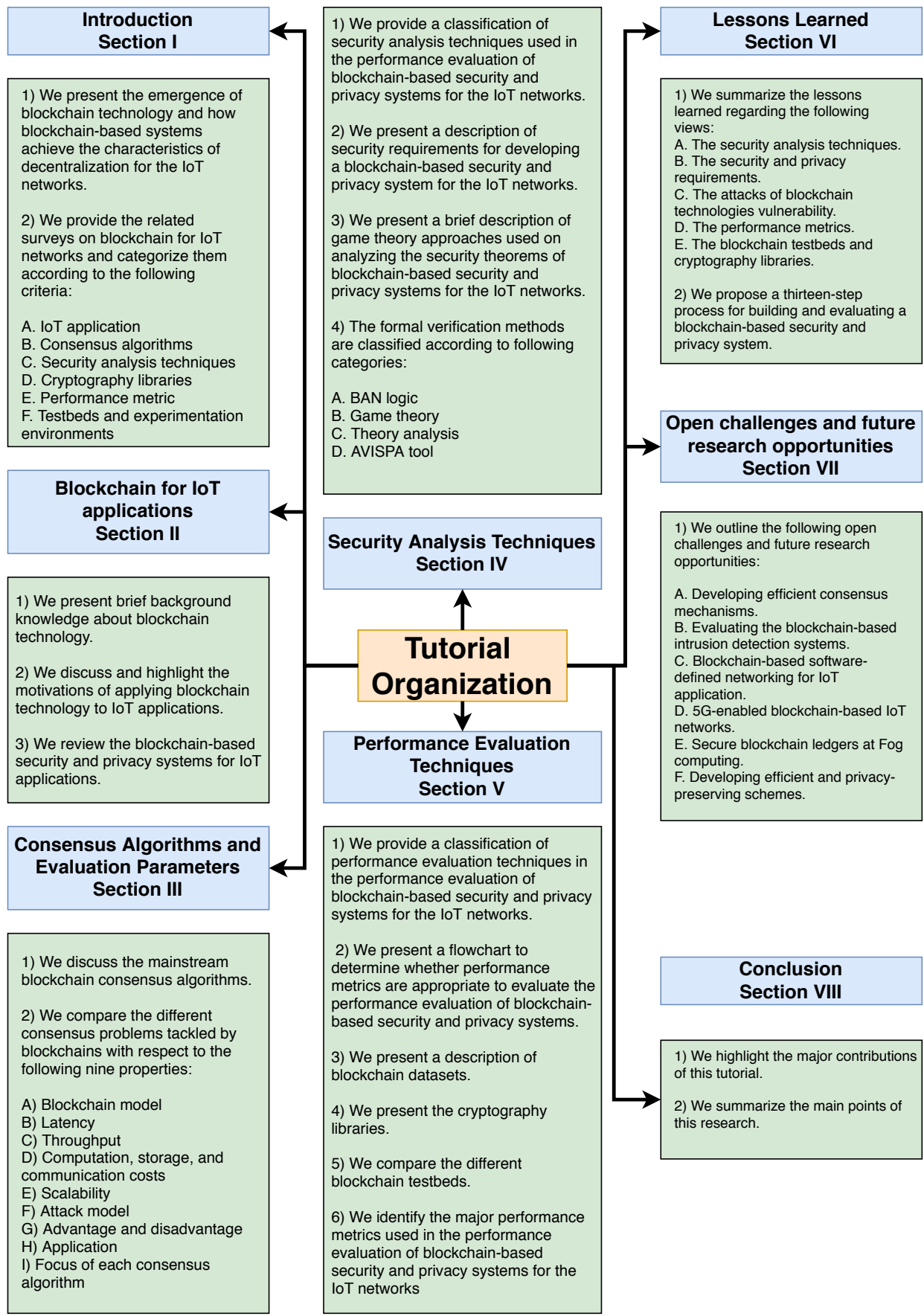
Fig. 1: Organization of the tutorial.

TABLE I: Related surveys on blockchain for IoT networks

| Reference | IoT application | Consensus algorithms | Security analysis techniques | Cryptography libraries | Performance metrics | Testbeds and experimentation environments |
|---|---|---|---|---|---|---|
| Kolb et al. [7] | No | Yes | No | No | Yes | No |
| Ferrag et al. [8] | Yes | Yes | No | No | No | No |
| Mehta et al. [9] | Yes | No | No | No | No | No |
| Belotti et al. [10] | No | Yes | No | No | No | Yes |
| Dai et al. [11] | Yes | Yes | No | No | No | No |
| Wu et al. [12] | Yes | Yes | No | No | No | No |
| Ferrag et al. [13] | Yes | No | No | No | No | No |
| Taylor et al. [14] | No | No | No | No | No | No |
| Bao et al. [15] | No | No | No | No | No | No |
| Mollah et al. [16] | No | Yes | No | No | No | No |
| Sengupta et al. [3] | Yes | No | No | No | No | No |
| Li et al. [17] | No | Yes | No | No | No | No |
| De Aguiar et al. [18] | No | Yes | No | No | No | No |
| Zhou et al. [19] | No | Yes | No | No | No | No |
| Our survey | Yes | Yes | Yes | Yes | Yes | Yes |

privacy systems for the IoT networks.

- *Cryptography libraries:* It indicates whether the survey described cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.
- *Performance metrics:* It indicates whether the survey described performance metrics used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.
- *Testbeds and experimentation environments:* It indicates whether the survey considered testbeds and experimentation environments used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

Most of the surveys on blockchain-IoT applications outline the countermeasures required for security and privacy without focusing on testbeds and experimentation environments. Some of them have limited their countermeasures covered to 3.0 applications [20], internet of energy management [21], cyber-physical systems [22], industrial internet of things [3], software defined networks [23], smart contracts formalization or [24]. Ferrag et al. [8] focused on security and privacy countermeasures, threats models, blockchain-based solutions for smart agriculture. Kolb et al. [7] presented a centralized tutorial that explains the fundamental elements of blockchains using Ethereum as a case study. Therefore, there are recent studies that compare the consensus algorithms for blockchain-based security and privacy systems [4], [25]–[29]. Xiao et al. [4] reviewed the consensus algorithms based on the five-component scheme, which consists of an incentive mechanism, block finalization, information propagation, block validation, and block proposal. Sadek Ferdous et al. [25] studied the consensus algorithms regarding four properties, including, performance, security, block & reward, and structural. Bodkhe et al. [26] analyzed the consensus algorithms for cyber-physical systems with respect to scalability and attacks, consensus finality, mining and consensus category, energy consumption, communication model and complexity, performance-related parameters, adversary tolerance model, and blockchain type. Lao et al. [27] compared the consensus algorithms based on eight properties, including, throughput, vulnerability, ad-

vantage, blockchain type, disadvantage, tolerated power of adversary, transaction finality, and system scalability.

To the best of our knowledge, our survey is the first that thoroughly covers consensus algorithms, security analysis techniques, cryptography libraries, performance metrics, and testbeds and experimentation environments used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

Our contributions in this work are:

- We review the blockchain-based security and privacy systems for IoT applications.
- We present the security analysis techniques and provide a classification into four categories, including, BAN logic, game theory, theory analysis, and AVISPA tool.
- We present various consensus algorithms and provide a comparison with respect to the following nine properties: a) blockchain model, b) latency, c) throughput, d) computation, storage, and communication costs, e) scalability, f) attack model, g) advantage and disadvantage, h) application, and i) focus of each consensus algorithm.
- We analyze the performance metrics used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.
- We provide the blockchain testbeds and cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems.
- We discuss the major steps to follow for building and evaluating blockchain-based security and privacy systems.
- We discuss and highlight open challenges and future research opportunities.

This tutorial article is organized into eight main sections, as shown in Fig. 1. Section II presents the blockchain-based security and privacy systems for seventeen types of IoT applications. In Section III, we analyze various consensus algorithms and evaluation parameters. In Section IV, we present the security analysis techniques and provide a classification into four categories. In Section V, we provide the performance evaluation techniques used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks. Then, we discuss the lessons learned in Section VI and highlight open challenges and future research

opportunities in Section VII. Lastly, Section VIII presents conclusions.
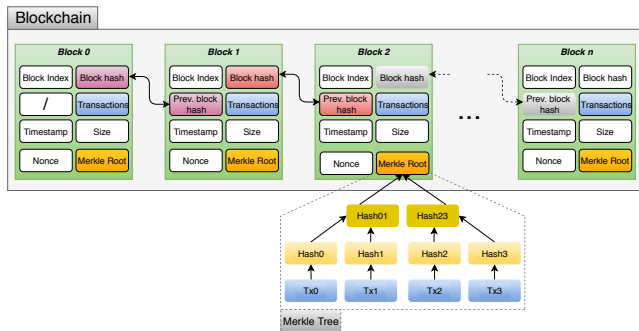


Fig. 2: The blockchain is composed of a list of consecutively-connected blocks.

## II. BLOCKCHAIN FOR IoT APPLICATIONS

The blockchain technology is used by the security and privacy systems for the IoT networks as a permanent, public, transparent ledger system for recording all transactions of data. This chain is a linear set of blocks, starting with a first block considered valid by default, which is called a genesis block, as presented in Fig. 2. The blocks are built and chained according to precise rules using a consensus algorithm, which is defined by the network. The validator prepares its block by collecting the new transactions, verifying that they follow the rules, and then including them in the block [13]. The data recorded in the blocks are considered very hard to change and become unforgeable after a period of time. A transaction is considered confirmed when it is included in a validated block. Each block has an identifier, which is a unique cryptographic hash of the data stored in the block [25]. In addition, a block consists of two parts: a block header and the transactions, used to build a Merkle tree. Specifically, a Merkle tree consists of hashing the transactions, then collecting the resulting in pairs and hashing them, and continuing until a single hash called the Merkle Root is obtained. Based on the cryptographic hash chain, this structure is very effective in proving that a complete chain of transactions has remained unchanged [4].

As illustrated in Fig. 3, the blockchain technology can be effectively applied in almost all domains of IoT. In this section, we review the blockchain-based security and privacy systems proposed for seventeen types of IoT applications.

### A. Internet of Vehicles

The blockchain technology is used by authentication schemes for the Internet of Vehicles as a distributed peer-to-peer network to manage the ledger that stores vehicle-related information. Noh et al. [30] developed a distributed data authentication system using blockchain technology for the Internet of vehicles, which vehicles are capable of authenticating and validating distributed broadcast data. The proposed system can prevent multiple insider attacks, in which two types of attacks are considered: passive and active. The passive attacks include sniffing, which does not disrupt or damage the target, while active attacks affect the target by falsifying information. Tan and Chung [31] proposed a secure authentication scheme with group key establishment, which is based on the consortium blockchain for vehicular networks. The proposed scheme develops the following three security strategies: a) Certificateless authentication strategy, b) Group key distribution strategy, and c) Dynamic group key updating strategy. The certificateless authentication strategy is used to solve the problem of key escrow in identity-based encryption for cloud-based VANETs with edge computing infrastructure. The group key distribution strategy is used for deploying consortium blockchain in decentralized vehicle-to-vehicle networks, while the dynamic group key updating strategy is used for dynamic updating using the Chinese remainder theorem.
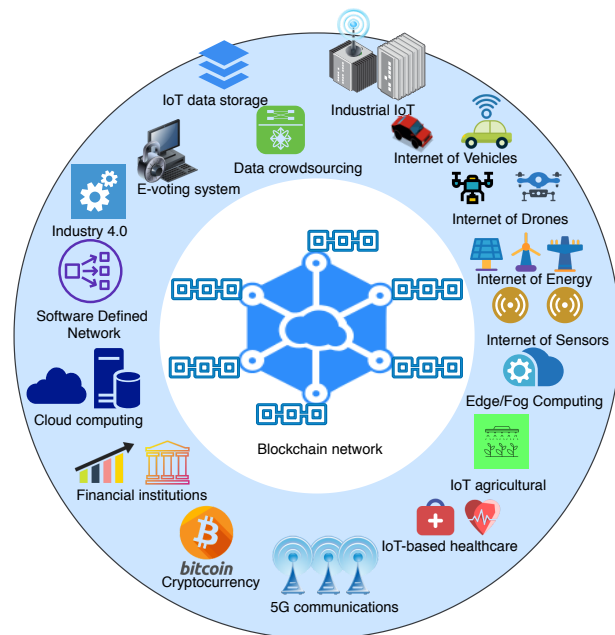


Fig. 3: Blockchain technology applied to seventeen types of IoT applications.

### B. Internet of Drones

With the help of the blockchain-based solution, the Internet of Drones overcomes the need for third-party systems to maintain trust as well as ensure high security to the drone communication network. The Internet of Drones has attracted growing attention and is projected to be an important supporting element of the future Internet of Things thanks to its significant benefits in terms of deployment flexibility, high flexibility of mobility and low cost. To broadcast and store the group's key messages in the internet of drones, Li et al. [32] designed a private blockchain, which is constructed by the ground control station. The drones are able to retrieve lost group keys securely and rapidly using a basic mutual healing protocol. To achieve privacy-preservation in drone-delivered services, Ferrag and Maglaras [33] designed an intrusion detection system with a delivery framework, called DeliveryCoin, which is based on bilinear groups and machine learning approaches. A UAV-aided forwarding mechanism is

adopted for achieving a consensus inside, while the machine learning approaches are used for detecting false transactions between self-driving nodes as well as detecting self-driving network attacks. Bera et al. [34] considered several drones deployed in different flying zones that communicate with each other, and the information is collected by the ground station server. To enable secure communication between the drones, but also between the drones and the ground station server, the authors introduced a secure blockchain-based access control scheme, in which the blocks are added using the ripple protocol consensus algorithm. Islam and Shin [35] integrated the mobile edge computing and proposed a blockchain-based data acquisition process for the unmanned aerial vehicles-assisted internet of things. Specifically, mobile edge computing is used for validates the data and the identity of the sender.

### C. Internet of Energy

The adoption of the blockchain framework for the Internet of Energy enables the protection of confidentiality, privacy, and integrity of electricity data. Sheikh et al. [36] designed a secured energy trading scheme between electric vehicles and the distribution network. For checking the blocks in the blockchain network, a Byzantine consensus algorithm is used for energy exchange between electric vehicles and the distribution network. The electric vehicles in a parking area can be involved in the process of exchanging energy with a distribution network according to its storage capacity and charging limits. For secure peer-to-peer (P2P) trading and decentralized scheduling within the energy management systems in local energy grids, Yang et al. [37] designed an automated demand response scheme, named ADR, which can increase the P2P trading security. To coordinate the consumption behaviors of responsive executors, the ADR scheme adopts a price-sensitive game-theoretic model and a smart contract mechanism. The ADR framework can coordinate actions and balancing supply and demand by taking into account the load transfer of plug-in electric vehicles, vehicle-to-grid support, and energy storage system. For privacy-preserving in wide-area (multi-area) smart grids, Kurt et al. [38] proposed a distributed dynamic state estimation mechanism. To protect against attacks and data manipulation, the proposed mechanism adopts the blockchain technology. The blockchain operates on the peer-to-peer network of local centers for detecting the measurement anomalies as well as misbehaving. To deal with the exchange of excess energy among neighboring nodes in the internet of energy, Ferrag and Maglaras [39] designed a blockchain-based scheme, named DeepCoin, which is based on bilinear pairing, short signatures, and hash functions to achieve privacy-preservation. The DeepCoin scheme adopts the practical Byzantine fault tolerance (PBFT) algorithm for build consensus inside blockchain-based energy network. For detecting fraudulent transactions and network attacks, the DeepCoin scheme uses an intrusion detection system based on recurrent neural networks.

### D. Cloud Computing

The existing cloud manufacturing concept can be combined with the blockchain technology, which the IoT devices can

be trusted without reliance on a trusted third party. Zhu et al. [40] proposed to integrate cloud manufacturing with blockchain technology in order to own both centralization and decentralization features. There two types of data stored in the blocks, namely, smart contracts and transactions. For global payment, the proposed system created the Cloud manufacturing cryptocurrency, which is based on two methods. One is allocating the Cloud manufacturing cryptocurrency to the initial miners by a genesis file, while the second is creating the Cloud manufacturing cryptocurrency with block rewards for miners. Wei et al. [41] proposed a blockchain data-based cloud data integrity protection mechanism, which is based on mobile agent technology. The proposed mechanism adopts a distributed virtual machine agent model that is deployed to the cloud. Specifically, the integrity framework based on the blockchain is built by the virtual machine proxy model, and the unique hash value for the file generated by the Merkel hash tree is used to control the data exchange by the smart contract, and the resulting data is delivered on time.

### E. IoT agricultural

The role of blockchain technology in IoT agriculture focuses on three keys, namely, supporting farmers in tracing food origins, enable peer-to-peer agricultural transactions through smart contracts, and guarantee agriculture data integrity [8]. Based on double chain architecture, Leng et al. [42] designed a public blockchain of the agricultural supply chain system, which can provide adaptive rent-seeking and matching mechanism for public service platform. Through elliptic curve cryptography, the proposed system ensures the transparency with security and privacy of transaction data. For the traceability and the certification of extra virgin olive oil, Arena et al. [43] proposed a blockchain-based application, named BRUSCHETTA, which can trace the production from the plantation to the shops. Therefore, production and sales records are often falsified. Shih et al. [44] use the blockchain to guarantee the authenticity of organic vegetables by proposing a marketing environment using Ethereum. The proposed scheme can increase organic vegetable sales and solve the issue of ecological agricultural pollution. To prevent distributed denial-of-service attacks in smart agriculture, Wu and Tsai [45] proposed an intelligent agriculture network security system, which is based on private blockchains. The proposed system applies the bilinear pairings technology to guarantees privacy and integrity in information transmission.

### F. IoT-based healthcare

Many researchers have tried to apply emerging blockchain technology into the field of healthcare for providing the security and privacy of healthcare data sharing. Wang et al. [46] proposed a framework of parallel healthcare systems, named PHSs, which is based on parallel execution approach, the artificial systems, and blockchain technology. The artificial systems are proposed to represent and model the static and dynamic characteristics of patients and doctors, while blockchain technology is used to facilitate the sharing of electronic health records, records review and auditability of care.

For transparent and secure information sharing in structure health monitoring, Jo et al. [47] introduced a blockchain-based distributed network, which smart contracts are constructed for autonomous decision making and control. The proposed network adopts the PoW consensus mechanism in combination with the SHA-256 hash function.
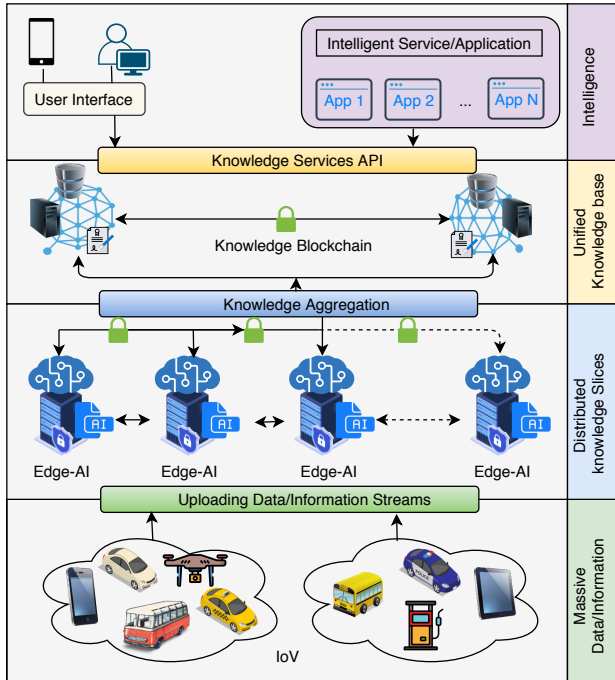


Fig. 4: Edge/Fog Computing architecture for blockchain-based IoT applications.

### G. IoT-based NFV/SDN

Software Defined Network (SDN) separates the network hardware from the control mechanism in order to allow easy control and management [48]. The SDN and Network Function Virtualization (NFV) can be coupled with blockchain technology for IoT networks. Therefore, an SDN/NFV architecture for blockchain-based IoT applications is based on four layers, namely, perception layer, data plane, virtualization and control plane, and blockchain layer. The perception layer consists of collecting the data from the environment (i.e., things). The data plane enables data transfer to and from the perception layer through IoT gateways. The virtualization and control plane is used to dynamically allocating resources to virtualized controllers. The blockchain layer plays the role of storing data, broadcast the mining and transaction information, and managing a P2P network using a consensus algorithm. To support the efficiency and security of IoT-based NFV/SDN, Rawat [49] combine three technologies, including, blockchain technology, software-defined networking, and edge computing. The ultimate goal of this combination is to decrease trade frictions and enhance transparency and trust between participants/stakeholders, as well as to enable a more transparent and dynamic exchange of spectrum and information technology resources in the emerging wireless network. Therefore,

Chaudhary et al. [50] combine Blockchain with SDN for intelligent transportation systems. Specifically, they proposed a Blockchain-based secure energy trading scheme, named BEST, which the SDN is used for transferring energy trading requests from electrical vehicles to the master controller. The BEST scheme uses blockchain to authenticating and validating participating in electrical vehicles. The SDN architecture adopted by the BEST scheme is composed of three planes, including, application, control, and data planes. This blockchain-based SDN architecture provides availability, integrity, confidentiality, and availability to network infrastructure.

### H. Edge/Fog Computing

The blockchain technology is applied for Edge/Fog Computing-based IoT networks to achieving the data recoverability property. The edge artificial intelligence-enabled internet of things is addressed by Lin et al. [51], which they proposed a peer-to-peer knowledge market scheme, which is shown in Fig. 4. The proposed scheme is secure and can provide knowledge management and trading. Therefore, the proposed scheme uses three news mechanisms, namely, proof of trading, smart contracts, and cryptographic currency knowledge coin. Based on the primitive of blockchain, Huang et al. [52] designed a fair three-party contract signing protocol for the decentralized fog computing environment. The proposed protocol allows members to contract equitably without the assistance of an arbitrator. Moreover, to protect the privacy of contract content, the proposed protocol adopts the threshold public-key encryption with verifiable encryption. For providing video streaming with mobile edge computing, Liu et al. [53] presented a blockchain-based mobile edge computing architecture, where small base stations deploy their computational and communication resources. Based on the transactional information on the blockchain, the components of the proposed architecture (i.e., users, base stations, and video providers) adapt their policies to allow a self-organized video broadcast and transcoding service to run without a centralized controller.

### I. Internet of Sensors

To provide decentralized and fine-grained authorization for the internet of sensors, Zhang et al. [54] designed a collaborative access control scheme, named ABAC, which is based on attributes. The ABAC scheme uses blockchain technology to produce a numeric account for each device to store the access attributes and policy that are used for authorization. When trustworthy collaboration is needed, the ABAC scheme adopts a controlled and verifiable collaboration mechanism, which can prevent unwanted collaboration. However, there are other challenges in the internet of sensors, namely, data sharing and Key-Leakage. To solve these challenges, Niu et al. [55] designed a blockchain-based key aggregation searchable encryption scheme, named BAI-KASE, for achieving data sharing in the internet of sensors. The BAI-KASE is proven secure under the decisional Diffie-Hellman assumption and Goldreich-Leivin Theorem. The BAI-KASE adopts a data-sharing system, which is based on private and public

TABLE II: Comparison between consensus algorithms used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

| Cons. | Model | Latency | Throughput | (C), (S), (Com) | Scalability | Attack model | (+) Pros (-) Cons | Application | Focus of this consensus |
|---|---|---|---|---|---|---|---|---|---|
| PoW | Permissionless | High | Low | (C) High (S) High (Com) Low | Low | Selfish Mining | + Resistant to falsification - Vulnerable to mining and corruption attacks | - Bitcoin | - Miners are competing to solve a computationally complicated math puzzle. - Each fog node at the fog computing layer are selected as miners. |
| BFT | Permissioned | Low | High | (C) Low (S) High (Com) High | Low | 33% vulnerability | + Fast and scalable with low transaction cost - High communication cost | - Tendermint | -Improves fault-tolerance using exploitation of communications between IoT devices and fog nodes. |
| PBFT | Permissioned | Low | High | (C) Low (S) High (Com) High | Low | 33% vulnerability | + High transaction throughput - High communication cost | - Hyperledger Fabric | - The fog nodes create PRE-PREPARE messages to propose to the other replicas the scheduling of the bloc. |
| FBA | Permissionless | High | High | (C) Low (S) High (Com) High | High | Reputation-based attacks | + Low transaction costs, network scalability, and high throughput - Trust requirements | - Stellar | - Use quorum slices to reach consensus. The quorum is a set of nodes sufficient to reach agreement. - The IoT node can appear on multiple quorum slices. |
| DBFT | Permissioned Permissionless | Low | High | (C) Low (S) High (Com) High | High | 33% vulnerability | + Fast and scalable with low computing cost - High communication cost | - Neo | - Allows for large scale collaboration in consensus through proxy voting in the sensors layer. |
| PoS | Permissionless | Medium | High | (C) Medium (S) High (Com) Low | Low | Service-based attacks | + Ensure the reliability of the system - Nothing-at-stake problem | - Peercoin - Nxt | - Users holding more currency are more chances to update the register of a blockchain. - All IoT nodes in the sensors layer are selected as the validators. |
| DPoS | Permissionless | Medium | High | (C) Medium (S) High (Com) Low | High | Manipulation-based attacks | + More scalable than PoW and PoS-based blockchains - Vulnerable to centralization | - BitShares - EOS | - Uses voting and election process. - Each fog node at the fog computing layer is selected as a delegate. |
| PoC | Permissionless | High | Low | (C) Low (S) High (Com) Low | Low | - Selfish Mining | + Can be used for malware detection and denial of service attack prevention - Lost disk space | - SpaceMint - Burstcoin | - Uses the disk idle space of computers in the local area for mining. - Each fog nodes at the fog computing layer are selected as miners. |
| PoET | Permissioned | Low | High | (C) Low (S) High (Com) Low | High | Reputation-based attacks | + Prevents high resource utilization - Not appropriate for public blockchains. | - Hyper-Ledger Sawtooth | - Each IoT device at the sensors layer generates a random wait time and sleeps for a fixed period of time. |
| PoA | Permissionless | Low | Low | (C) Low (S) High (Com) Low | High | Reputation-based attacks | + Less computational overhead - Trust requirements | - VeChain | - New blocks can only be generated by nodes with authority. - Select all fog nodes in fog computing layer as validators. |
| PoWe | Permissionless | Medium | Low | (C) Medium (S) High (Com) Low | Low | Service-based attacks | + Ensure the reliability of the system - Nothing-at-stake problem | - Algorand | - The proportion of coins owned in the sensors layer refers to the probability of finding the next block. |
| PoAc | Permissionless | High | Low | (C) High (S) High (Com) Low | Low | Selfish and reputation-based behaviors (e.g., Selfish Mining) | + Resistant to falsification - Vulnerable to mining and corruption attacks | - Decred | - Miners are competing to solve a computationally complicated math puzzle. - A group of fog nodes in the fog computing layer is selected randomly as validators for validating or signing the new block. |
| DAG | Permissioned | Medium | High | (C) Medium (S) Medium (Com) High | High | Cryptanalytic attacks | + High scalability with energy efficient - High communication costs | - Byteball - HashGraph - Iota | -A set of the transactions added to the Tangle's DAG are selected as valid by a fog node called Coordinator. |

(C) Computation, (S) Storage, (Com) Communication

blockchain with Proof of Work (PoW) consensus mechanism and Practical Byzantine Fault Tolerance Algorithm (PBFT).

To provide reliable auditing of user's access history in the internet of sensors (i.e., Smart Homes), Lin et al. [56] designed a blockchain-based secure mutual authentication system, named HomeChain, that can be implemented in intelligent home systems. Based on the Elliptic Curve Integrated Encryption Scheme (ECIES), the HomeChain system provide confidentiality of the transmitted message, including, the response data and the request transaction data. To enable a group member to anonymously request remote access or control, the HomeChain system adopts the group signatures.

## III. CONSENSUS ALGORITHMS AND EVALUATION PARAMETERS

Consensus algorithms are a critical part of each blockchain IoT network since they are responsible for ensuring the integrity and security of these distributed systems. Therefore, the decentralized public IoT blockchains are implemented as distributed systems and since they are not under the control
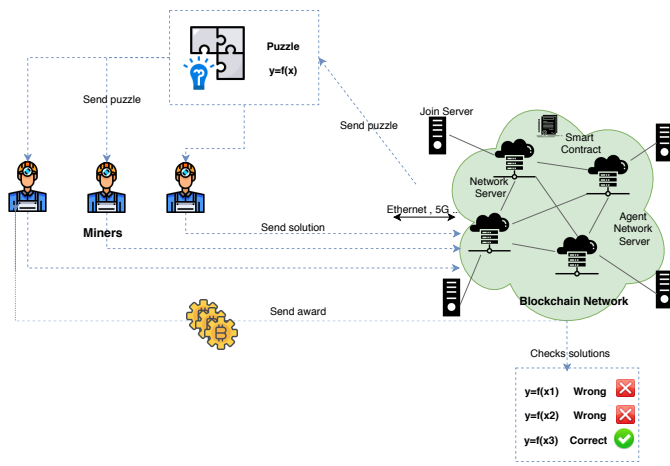
Fig. 5: Proof-of-Work (PoW) consensus algorithm, where miners competing to solve a computationally complicated math puzzle in order to perform transactions on the blockchain network and are rewarded afterward.
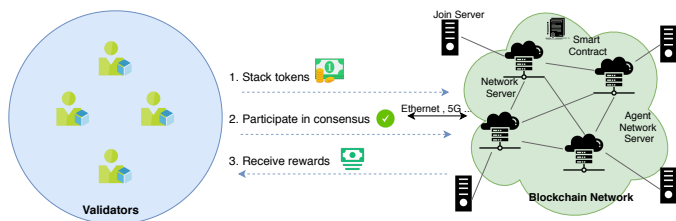


Fig. 6: Proof-of-Stake (PoS) consensus algorithm, where validators can produce the next block based on their stake.

of a central authority, the distributed nodes are required to agree on the validity of the transactions [57]. This is where consensus algorithms are involved. Specifically, a consensus algorithm ensures that protocol rules are followed and that all transactions are reliably processed.

### A. Consensus Algorithms

There are several types of consensus algorithms for blockchain-based security and privacy systems [27], [28], as presented in Fig. 7. Each consensus algorithm has advantages and disadvantages when attempting to achieve a successful balance between scalability, security, and functionality.

*1) Proof-of-Work (PoW):* The PoW algorithm was introduced by Nakamoto [58]. It is designed first to minimize jamming emails and then implemented by Bitcoin. The PoW algorithm is used to confirm transactions and produce new blocks in the blockchain-based security and privacy systems. Specifically, there are IoT nodes, called miners, competing to solve a computationally complicated math puzzle in order to perform transactions on the blockchain network and are rewarded afterward, as presented in Fig. 5. The blockchain-based security and privacy systems that use PoW as a consensus algorithm become resistant to falsification due to the high cost of calculation. Nevertheless, a blockchain system running PoW may also be attacked in the mining operation in

which an attacker can gain more profit by launching mining and corruption attacks [27].

*2) Byzantine Fault Tolerant (BFT):* This is a well-known issue in distributed computing which is typically solved with Byzantine generals. The issue is that a group of Byzantine generals with different parts of the Byzantine forces have circled a city. They should agree in agreement whether to launch an attack or not. When certain generals launch an attack alone, it will end in tragedy for their siege. The generals are mostly split by distance and are required to transmit some messages in order to communicate. The blockchain-based security and privacy systems that use BFT as a consensus algorithm become fast and scalable but it used usually for private and permissioned IoT networks [59].

*3) Practical Byzantine Fault Tolerance (PBFT):* It is one solution to the Byzantine generals problem, proposed by Castro et al. [60], which consists of a minimum of $3f+1$ nodes in order to tolerate $f$ defective nodes. The blockchain-based security and privacy systems that use PBFT as a consensus algorithm will have high transaction throughput, but they are centralized and permissioned.

*4) Federated Byzantine Agreement (FBA):* It is another solution to the Byzantine generals problem, where each byzantine general is responsible for their own blockchain. The FBA consensus is used by Stellar and Ripple [61] which they use quorum slices to reach consensus. The blockchain-based security and privacy systems that use FBA as a consensus algorithm will have low transaction costs, network scalability, and high throughput, but there are trust requirements that should to archives.

*5) Delegated Byzantine Fault Tolerance (DBFT):* This consensus was introduced by NEO, which provides a fault tolerance of $f = [(n-1)/3]$ for blockchain-based security and privacy system composed of $n$ nodes. The DBFT consensus is similar to Delegated Proof-of-Stake that allows for large scale collaboration in consensus through proxy voting. The blockchain-based security and privacy systems that use DBFT as a consensus algorithm will have network scalability, high throughput, and high transaction costs.

*6) Proof-of-Stake (PoS):* To address the issues inherent in PoW, the PoS consensus was developed as an alternative. Specifically, the PoS consensus is based on a completely different approach than PoW and requires no special computing power [62]. Rather than use mining, there should be a certain stake (coins) in the system. More this amount is important, more chances a node will be chosen to update the register of a blockchain, as presented in Fig. 6. The blockchain-based security and privacy systems that use PoS as a consensus algorithm will have the advantage that no large quantities of energy are required to secure a blockchain, but it is vulnerable to the nothing-at-stake problem.

*7) Delegated Proof of Stake (DPoS):* This consensus aims to address the weaknesses of PoS and PoW by proposing a hybrid model. The DPoS consensus operates on the same basic principle as PoS. The IoT nodes in charge of forging blocks must be elected by the community members. The election system ensures that the blockchain is not controlled by a minority of nodes, as can be the case of a miner with a large
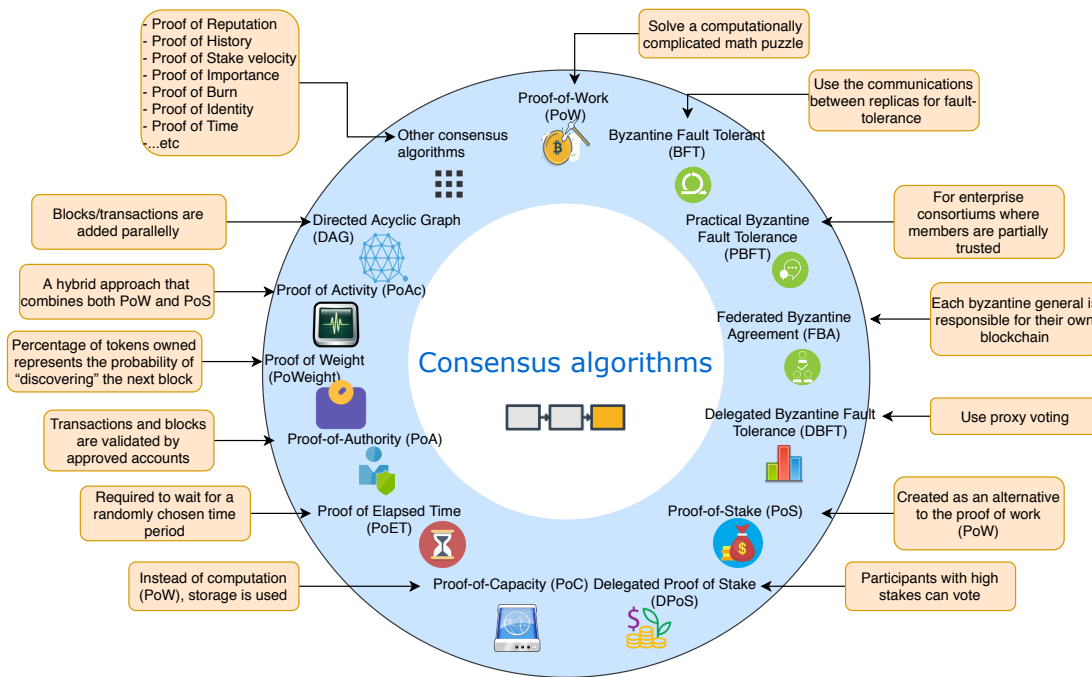
Fig. 7: Several types of consensus algorithms for blockchain-based security and privacy systems.

amount of computing power or a PoS forger with a very large amount of tokens [63]. The blockchain-based security and privacy systems that use DPoS as a consensus algorithm will have the advantage to define a fully participative organization.
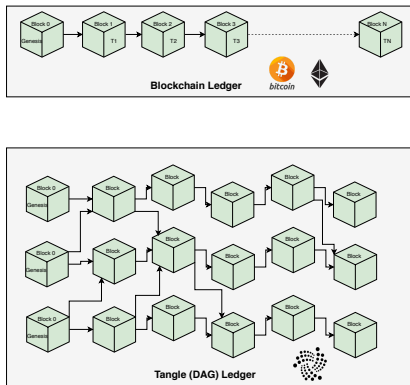


Fig. 8: Difference between Blockchain & Tangle ledgers.

*8) Directed Acyclic Graph (DAG):* Unlike the linear structure that is basically adopted by any blockchain system, the DAG consensus applies an alternative approach to adding the blocks based on parallelism. Specifically, the blocks/transactions are not concatenated in a chained list but in a hierarchy tree [64], as shown in Fig. 8. There are some popular projects which use DAG consensus, including, RaiBlocks/Nano, Byteball, HashGraph, and Iota. The blockchain-based security and privacy systems that use PoAc as a consensus algorithm will have high scalability with high communication costs.

*9) Other consensus algorithms:* More consensus algorithms are available which can be adapted by blockchain-based security and privacy systems for IoT networks. The following consensus algorithms are cited: Proof of Reputation, Proof of History, Proof of Stake velocity, Proof of Importance, Proof of Burn, Proof of Identity, Proof of Time, Proof-of-Capacity, Proof of Elapsed Time (PoET), Proof-of-Authority (PoA), Proof of Weight (PoWeight), and Proof of Activity (PoAc).

*B. Evaluation Parameters*

In the literature, there are recent studies that compare the consensus algorithms for blockchain-based security and privacy systems [4], [25]–[29]. Therefore, in this tutorial, we compare the consensus algorithms with respect to the following nine properties:

- Blockchain model: The blockchain-based security and privacy systems for the IoT networks can be divided into two different categories, namely, permissioned and permissionless. Permissioned blockchains require access to be allowed to be part of the network. There are three types of blockchain permissioned ledger technologies, including, public blockchains, federated/consortium blockchains, and private blockchain. However, the permissionless blockchains require no authorization to access and communicate with, which means that anyone can join the network.
- Latency: This metric indicates the time taken to create the next block of transactions in the blockchain network.
- Throughput: This indicates two metrics, namely, a) read throughput and 2) transaction throughput. The read throughput is a metric of the total number of reading transactions performed within a defined period of time. The transaction throughput is the ratio of valid transactions that are initiated by specific configurations of the blockchain within a defined period of time.

- Computation, storage, and communication costs: The blockchain-based security and privacy systems for the IoT networks can be categorized based on performance metrics, such as, computation cost, storage cost, and communication cost.
- Scalability: This metric indicates two main scalability problems, namely, a) The time required to insert a transaction in the block, and b) The time required to reach a consensus.
- Attack model: This metric shows the vulnerability of the blockchain-based security and privacy systems for the IoT networks in case of failures. In this tutorial, we use the threat models presented in the study [13]. Specifically, the threat models against blockchain networks are categorized into five main categories, namely, service-based attacks, reputation-based attacks, identity-based attacks, manipulation-based attacks. The service-based attacks include collusion attack, double-spending attack, refusal to sign attack, and DDoS/DoS attack. The reputation-based attacks include whitewashing and hiding blocks attack. The cryptanalytic attacks include quantum attacks. The identity-based attacks include sybil attack, impersonation attack, replay attack, and key attack. The manipulation-based attacks include man-in-the-middle attack, modification attack, overlay attack, tampering attack, and false data injection attack.
- (+) Pros (-) Cons: This metric indicates the important advantage and disadvantages of each consensus algorithm by considering the security level and performance-related parameters.
- Application: This presents the available projects that use each consensus algorithm.
- Focus of the consensus algorithm: This indicates the basic idea of each consensus algorithm.

Tab. II presents the comparison between consensus algorithms used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks. Regarding the scalability and high transaction time cost, the PoS, DAG, FBA, PoET, DPoS, and DBFT provide high performance. The PoW, FBA, PoC, PoAc provide high latency with security levels. Therefore, from the table, we can see that each consensus algorithm has several different levels of advantages and disadvantages, which means that they are suitable for different situations.

## IV. SECURITY ANALYSIS TECHNIQUES

To evaluate and analyze the security of blockchain-based systems for the IoT networks, security researchers use the following formal security techniques: BAN logic, Game theory, Theory analysis, ProVerif tool, and AVISPA tool, as presented in Tab. III.

### A. Formal verification method

*1) Burrows, Abadi, and Needham (BAN) logic [98]:* is a widely used analysis model for identity authentication protocols. Noh et al. [30] verify the correctness of their proposed

TABLE III: Security Analysis Techniques used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

| Year | Scheme | IoT application | Security analysis technique |
|------|--------|-----------------|------------------------------|
| 2021 | Vangala et al. [65] | IoT agricultural | AVISPA tool |
| 2021 | Xu et al. [66] | Internet of Vehicles | ProVerif tool |
| 2020 | Noh et al. [30] | Internet of Vehicles | BAN logic |
| 2020 | Cheng et al. [67] | IoT-based healthcare | BAN logic |
| 2020 | Wilczyński et al. [68] | Cloud computing | Game theory |
| 2019 | Lai et al. [69] | Internet of Vehicles | Theory analysis |
| 2019 | Luo et al. [70] | Internet of Vehicles | Theory analysis |
| 2019 | Yao et al. [71] | Internet of Vehicles | Theory analysis |
| 2019 | Zhang et al. [72] | IoT-based cryptocurrency | Theory analysis |
| 2019 | Bera et al. [34] | Internet of Drones | AVISPA tool |
| 2019 | Yang et al. [37] | Internet of Energy | Game theory |
| 2019 | Zhang et al. [73] | Edge/Fog computing | Game theory |
| 2019 | Lin et al. [56] | Internet of Sensors | Theory analysis |
| 2019 | Lin et al. [51] | Edge/Fog computing | Game theory |
| 2019 | Wang et al. [74] | Edge/Fog computing | Game theory |
| 2019 | Qiu et al. [75] | Internet of Drones | Game theory |
| 2019 | Li et al. [76] | Internet of Energy | Game theory |
| 2019 | Liu et al. [53] | Edge/Fog computing | Game theory |

system formally, which they use BAN logic based on the following four steps: a) idealization, b) assumptions, c) goals, and d) verification. The idealization concerns the form of the data. The assumptions concern the relationship between entities and keys. The goals concerns traceability, non-repudiation, strong privacy preservation, and message integrity. The verification concerns the prove of the hypotheses with the rules of the BAN logic. Cheng et al. [67] use BAN Logic to analyze the correctness of the medical data sharing scheme for medical cyber-physical systems.

*2) Game theory:* Game theory is a natural approach to addressing competition and decentralized decision-making in the Internet of Things. Tan and Chung [31] use the game theory for analyzing the security theorems of their scheme in terms of the unforgeability against adaptive chosen message attack, resistance to replay attack during authentication phase, preventing unauthorized tracking to specified vehicles, and provide certificateless authentication property. These terms are defined through the games with random oracles by operating the queries from the adversary and the challenger. Therefore, Cheng et al. [81] analyze the incentive mechanism used in their semi-centralized scheme with a game theory model. Specifically, they define two-time cost, including, travel time as $\omega(\omega > \mu > 0$ and interaction time as $\mu(\mu > 0)$.

- **Stackelberg game:** is a non-symmetrical game, in which a player named leader has a preferred position and decides first, when the remaining players - the followers - follow his actions. Qiu et al [75] used a game-theoretic approach, called Stackelberg, to perform the spectrum trading and operations among the buyer and seller. Specifically, a Stackelberg game is a strategic game that involves a leader and multiple trackers in competition with each other over some resources. In the proposed scheme, the authors formulate the mobile network operator as the leader and the unmanned aerial vehicle operators as the trackers. Li et al. [76] used a Stackelberg game for modeling the energy allocation between microgrids and miners in the internet of energy. The microgrid is consid-

TABLE IV: Cryptography Libraries used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

| Year | Scheme | Cryptography library | Type | Program. language | IoT application | Focus of this work |
|---|---|---|---|---|---|---|
| 2020 | Eltayieb et al. [77] | PBC library [78] | Pairing-based cryptography library | C | Cloud computing | Evaluate the characteristics of computational complexity |
| 2020 | Nkenyereye et al. [79] | Crypto ++ library [80] | Cryptographic schemes | | Edge/Fog Computing | Evaluate the characteristics of computation and communication overhead |
| 2019 | Cheng et al. [81] | libbswabe-0.9, ibrary bcprov-jdk15on-158, jpbc-plaf-1.2.1, jpbc-api-1.2.1, and commons-codec1.7 | Elliptic curve library | Java Runtime Environment 1.8 | Internet of Vehicles | Construct bilinear pairs using the elliptic curve |
| 2019 | Luo et al. [70] | ECC-secp256k1 and ECDSA-secp256k1 | Elliptic curve library | JAVA language | Internet of Vehicles | Evaluate the characteristics of computational overhead and security |
| 2019 | Ali et al. [82] | The MIRACL library [83] | Pairing-based cryptography library | C/C++ | Internet of Vehicles | Perform mathematical operations underlying Pairing-based cryptography library |
| 2019 | Li et al. [32] | ECC-secp256k1 and ECDSA-secp256k1 | Elliptic curve library | JAVA language | Internet of Drones | Evaluate the characteristics of computation and communication overhead |
| 2019 | Xie et al. [84] | Crypto ++ library [80] | Cryptographic schemes | C++ | IoT in the 5G era | Evaluate the transmission delay |
| 2019 | Niu et al. [55] | MIRACL library [83] | Pairing-based cryptography library | C/C++ | Internet of Sensors | Evaluate the performance of blockchain-based key aggregation searchable encryption |
| 2019 | Zhang et al. [72] | MIRACL library [83] | Pairing-based cryptography | C/C++ | IoT-based Cryptocurrency | Evaluate the performance of linkable group signature |
| 2019 | Li et al. [85] | MIRACL library [83] | Pairing-based cryptography | C/C++ | IoT-based Cryptocurrency | Analyze the computational cost of the traceability |
| 2018 | Jo et al. [47] | Secp256k1 signature code | Elliptic curve library | N/A | IoT-based healthcare | Evaluate the characteristics of average throughput and Bbock size against transactions/s |
| 2018 | Lin et al. [86] | PBC library [78] | Pairing-based cryptography library | C | Industry 4.0 | Investigate the time cost of cryptographic algorithms |

ered as a game leader that offers a non-uniform pricing strategy for different miners. Wilczyński and Kołodziej [68] formally modeled schedule confirmation/approval using the Stackelberg game model for blockchain-based cloud computing. In the blockchain-based cloud model, the leader is the node, which initiates a transaction, and the follower is the next node in the sequence of nodes in the blockchain network. Liu et al. [53] formulated the video transcoding and delivery problem as a three-stage Stackelberg game for blockchain-based mobile edge computing.

- **Noncooperative game:** Yang et al. [37] modeled a noncooperative game to achieve decentralized scheduling of multiple responsive executors in the energy local networks, which is based on three components, namely, a) Players, b) Strategy Space, and c) Utility Function. The players include all the users of plug-in electric vehicles and battery energy storage. The strategic space includes a collection of achievable patterns of consumption that reduce the utility function of the players, while the utility function includes the measurement of the players' cost in the game. In order to minimize the cost of each mobile equipment for mobile edge computing, Zhang et al. [73] modeled the joint coin-loaning and computation-offloading issue as a noncooperative game, in which the mobile equipments can perform distributed decision making. Lin et al. [51] proposed an optimal knowledge pricing strategy based on a noncooperative game to study the quality knowledge related knowledge sellers for edge artificial intelligence-enabled internet of things.
- **Differential game:** is a game that involves $N$ players, each one solving an optimal control question, where the other players also solving their optimal control questions.

These questions are related since the controls selected by each player affect the evolution of the state variables [99]. Wang et al. [74] uses the differential game to model the introduction of blockchain technology in traditional fog computing.

*3) Theory analysis:* Lai et al. [69] uses theory analysis to prove that their scheme can achieve a series of design objectives, namely, a) provide effective and fair incentives, b) secure and privacy-preserving, and c) ensure the reliability of map update. Luo et al. [70] uses theory analysis to prove that their scheme can preserve vehicles' location privacy and resilience to various trust model attacks (such as Sybil attack, on-off attack, Whitewashing attack, and bad-mouthing attack). Yao et al. [71] analyze the security features of the IDaaSoVCC scheme based on two assumptions, namely, discrete logarithm assumption and decisional bilinear diffie-hellman assumption, which can satisfy identity information privacy, confidentiality, and forward secrecy. In the random oracle model, Zhang et al. [72] prove that the linkable group signature can achieve likability, full-traceability, and full-anonymity for IoT-based cryptocurrency.

*4) AVISPA tool:* [100] is used as a formal security verification tool for authentication schemes that used a language called the High-Level Protocol Specification Language (HLPSL). Bera et al. [34] adopted the AVISPA tool to prove the security of their scheme with the implementation of three basic roles, namely, the role for the drone, the role for the ground station server and the role for the cloud server.

### B. Security requirements

For developing a blockchain-based security and privacy system for the IoTs networks, the following security requirements are fundamental to be achieved:
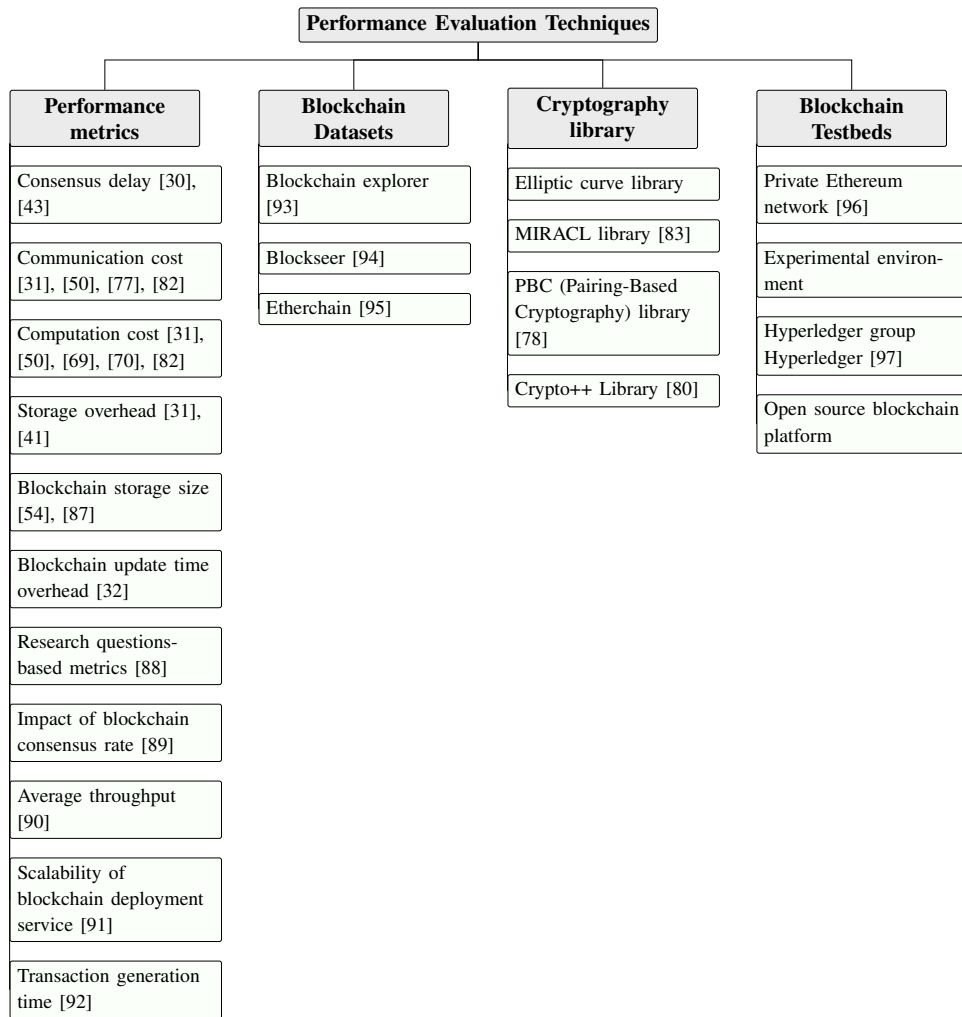
Fig. 9: Classification of Performance Evaluation Techniques in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

- **Privacy:** Consists to prevent the revelation of personally identifiable information based on data containing private and sensitive information (e.g., medical images in medical IoT systems) [30], [87], [92], [101], [102].
- **Integrity:** The IoT data that is generated and transmitted over the IoT network should not be monitored and altered during communication [69]–[71], [79], [81].
- **Authentication:** Each IoT device that participates in transmitting the IoT data should be authenticated before it is authorized to join the blockchain-based security and privacy system [69]–[71], [82].
- **Non-repudiation:** This constitutes irrefutable proof of the validity and origin of all data transmitted, where an IoT device cannot refuse any participation in the IoT data reporting [30], [79], [81].
- **Traceability:** The blockchain-based security and privacy system should be able to provide identity privacy preservation conditionally in the IoT network. The tracing authority is able to trace and reveal the real identity of malicious IoT devices through its database [72], [75], [81], [82].

- **Identity privacy:** Consists to ensure that the malicious IoT devices cannot learn the identity information from the proof during the data integrity checking process [31], [70], [71], [82].
- **Location privacy:** The blockchain-based security and privacy system should be able to preserve devices' location privacy during the anonymous communication process [70].
- **Scalability:** The blockchain-based security and privacy system should be able to adapt to rapid growth in terms of both the number of participants and the volume of IoT data shared.
- **Unforgeability:** Guarantees that malicious devices cannot even produce a new signature for an already signed message in the IoT network [103].
- **Anonymity:** The blockchain-based security and privacy system should be able to guarantee the anonymity of users in the IoT network. In other words, the adversary cannot obtain the real identity of the user by analyzing the transactions [56], [81].
- **Trust management:** It depends on the specific use cases

where trust management is to be applied. Kochovski et al. [104] presented several relevant trust-related attributes in a blockchain-based fog computing platform, such as availability, credibility, and privacy.

- **Access control:** This constitutes to regulates the IoT devices that can connect or use resources in an IoT environment. The blockchain-based security and privacy system should be able to perform identification authentication and authorization of users [34], [54], [86], [105], [106].
- **Data reliability:** The blockchain-based security and privacy system should be capable of protecting IoT data from suppression or falsification by possible attacks. In addition, the system should be able to store replicated data to ensure reliability in the case of a single-point fault.
- **Perfect forward secrecy:** For the security of the previously transmitted data, the blockchain-based security and privacy system should ensure that session keys cannot be compromised if the server's private key is compromised [56].
- **Confidentiality:** Only the IoT devices involved in the blockchain-based security and privacy system are allowed to know the content of the smart contract [52], [75], [88].
- **Data auditability:** The smart contracts that are saved in the blockchain-based security and privacy system should be securely kept and easily verifiable. Although an IoT device in the blockchain network can be compromised, the malicious IoT device should not be able to modify and upload any smart contract [79], [107].
- **Unlinkability:** The blockchain-based security and privacy system should be able to ensure that the various operations of the particular user should not be linked together [103].

## V. PERFORMANCE EVALUATION TECHNIQUES

Fig. 9 presents the classification of performance evaluation techniques in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

### A. Performance metrics

Tab. V presents the performance metrics and cryptography technologies used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

*1) Consensus delay (Latency):* is defined as the time taken for the transaction to be approved and published. Arena et al. [43] uses this metric for evaluating the performance evaluation of BRUSCHETTA application, which is defined as the delay between generating a transaction and its publication on the blockchain. Noh et al. [30] used consensus delay as a performance metric for evaluating the processing time of the consensus algorithm in a blockchain-based system for the internet of vehicles. The consensus delay is used also for comparing the overhead analysis with two conventional algorithms such as hotstuff consensus and loof-fault tolerance. Ferrag and Maglaras [33] analyzed latency of blockchain consensus of the proposed DeliveryCoin and the Prime-based DeliveryCoin

under a number of UAVs, probabilities of malicious UAV nodes, and velocities of UAV nodes. Zhou et al. [112] use the consensus latency as a performance metric for evaluating the performance of a blockchain-based personal healthcare information system, which is composed of three parts: the time to generate consensus identities, the time for consensus messages to propagate, and the time to count consensus votes.

*2) Communication cost:* Tan and Chung [31] analyzed the communication cost of the proposed authentication scheme, which they calculate the required communication rounds for VANET authentication in RSU side. The communication cost includes the system parameter set, authentication request, and acknowledgment message. The communication cost of the proposed authentication scheme demonstrating that fewer communication rounds are required comparing with PATF [113] and EPFA [114]. Ali et al. [82] analyzed the communication costs of CL-PKS scheme by considering the size of the parameters such as certificateless-signature of the vehicle, current timestamp, public key, and pseudo-identity. Eltayieb et al. [77] analyzed the communication cost of the blockchain-based attribute-based signcryption scheme for the cloud environment, which includes the size of the signing key, decryption key, and ciphertext. Therefore, Chaudhary et al. [50] analyzed the communication cost of a blockchain-based secure energy trading scheme for IoT-based NFV/SDN, which includes the size of identity key and hash values for an electric vehicle, transaction server, and miner node.

*3) Computation cost (ms):* Tan and Chung [31] analyzed the computation cost of the proposed authentication scheme, which they calculate the point multiplication, the pairing operation, and the employed secure hash functions in the RSU and vehicle side. The approximate execution time compared PATF [113] and EPFA [114] shows less computation overhead for resource-limited vehicles. Lai et al. [69] calculates the time complexity of running their scheme which is equal to $O(n\log n)$. Luo et al. [70] focus on the computational complexity of the vehicle (i.e., requester vehicle, cooperative vehicle without response, and cooperative vehicle providing assistance), in which the construction process involves signature $O(Sig)$, verification $O(Sig')$, encryption $O(Enc)$, and decryption $O(Enc')$. Ali et al. [82] analyzed the computation cost of CL-PKS scheme in the signing of messages and in the verification of the corresponding signature, which the results show approximately 7.6361 ms. Chaudhary et al. [50] analyzed the computation time of a blockchain-based secure energy trading scheme for IoT-based NFV/SDN, which is computed on the basis of the operations in the blockchain, such as SHA-1 and the addition operation.

*4) Storage overhead (bits):* Tan and Chung [31] used storage cost as a performance metric for evaluating the storage overhead of RSU and individual vehicles during the authentication phase. The storage cost consists of the length of the identity, the elements in a cyclic additive group, and the delivered session key. Compared to PATF [113] and EPFA [114], Tan and Chung's scheme shows less storage overhead. Wei et al. [41] studied the storage cost of a blockchain data-based cloud data integrity protection mechanism, which is the sum of the verification tree storage costs.

TABLE V: Performance Metrics and Cryptography Technologies used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

| Year | Scheme | IoT applications | Cryptography technology | Consensus algorithm | Performance metric | (+) Pros (-) Cons |
|------|--------|------------------|-------------------------|---------------------|--------------------|--------------------|
| 2020 | Shen et al. [108] | IoT data storage | - Homomorphic cryptosystem and Paillier | PoW consensus mechanism | - Time consumption (s) <br> - Accuracy (%) | + Confidentiality of the sensitive data <br> - The proposed scheme is not evaluated with cyber attack datasets. |
| 2020 | Ma et al. [109] | Data crowd-sourcing | - Ciphertext-policy attribute-based encryption <br> - Hash function | N/A | - Cost of smart contracts (USD) <br> - Cost for running data trade (USD) | + Fine-grained authorization <br> - Data reliability is not considered |
| 2020 | Zhang et al. [54] | Internet of Sensors | - Ellipse curve cryptography <br> - Hash function | Solo consensus algorithm | - Computational cost <br> - Storage overhead for IoT devices (bytes) <br> - Time cost (ms) | + Provide credible credentials <br> - Non-repudiation is not considered |
| 2020 | Zhu et al. [40] | Cloud Computing | Public key and SHA256 | Open-source consensus standards | - Transaction overhead (USD) <br> - Average number of transaction per second | + Own both centralization and decentralization features <br> - Whitewashing attack is not analyzed |
| 2020 | Liu and Zhang [110] | IoT data storage | - Ellipse curve cryptography asymmetric algorithm <br> - Hash function | Equity-based proof of stake (PoS) | - Speed of encryption (min) <br> - Time complexity (s) <br> - Encryption accuracy (%) | + ECC encryption algorithm is efficient compared to RSA and DSA algorithms <br> - Anti-key-leakage attack is not analyzed |
| 2020 | Kabra et al. [111] | Financial institutions | - QR based authentication algorithm | Proof-of-Authority (PoA) | - Communication cost <br> - Computation time | + Provenance and auditability attacks <br> - Non-repudiation is not considred |
| 2020 | Noh et al. [30] | Internet of Vehicles | - Message authentication code <br> - Ellipse curve cryptography <br> - Advanced encryption standard | PBFT consensus algorithm | - Consensus delay | + Authenticate the broadcast data in a distributed manner <br> - Sybil attack is not analyzed |
| 2020 | Nkenyereye et al. [79] | Edge/Fog Computing | Signcryption scheme without bi-linear pairings <br> - Hash function | Proof of stake consensus algorithm | - Computational cost <br> - Signcryption/Designcryption time (s) <br> - Communication cost | + Achieves the confidentiality and integrity <br> - Location privacy is not considered |
| 2019 | Tan and Chung [31] | Internet of Vehicles | - Ellipse curve cryptography <br> - Hash function <br> - Chinese remainder theorem | N/A | - Communication cost <br> - Computation cost (ms) <br> - Storage overhead (bits) | + Enables accurate group management in a distributed manner <br> - Trust and access control are not considered |
| 2019 | Lai et al. [69] | Internet of Vehicles | - Randomized RSA-based partially blind signature <br> - Pseudonym management mechanism <br> - One-way hash function | N/A | - Computational complexity <br> - The influence of the number of users on the amount of data | + Ensure completion quality and achieve payment control for vehicle users <br> - Double spending and 51% attacks are not analyzed |
| 2019 | Cheng et al. [81] | Internet of Vehicles | - Ciphertext policy attribute-based encryption <br> - Hash function <br> - Digital Signature | Cooperation consensus algorithm | - Time consumption (ms) | + Manage fine-grained noninteractive access control on traffic data <br> - Bad-mouthing attack is not analyzed |
| 2019 | Qiu et al [75] | Internet of Drones | - Elliptic curve digital signature algorithm <br> - Asymmetric cryptography <br> - Hash function | Distributed consensus algorithm | - Impact of spectrum coins and spectrum demands | + Without reliance on a trusted intermediary <br> - Location privacy and scalability are not considered |
| 2019 | Xie et al. [84] | IoT in the 5G era | - SHA-256 hash function | Proof-of-work and proof-of-stake | - Transaction transmission delay <br> - Video encryption time overhead | + Malicious vehicular nodes are detected <br> - Whitewashing attack is not analyzed |
| 2019 | Chaudhary et al. [50] | IoT-based NFV/SDN | - SSL/TLS connection <br> - Hash function | PoW consensus mechanism | - Communication cost <br> - Computation time | + Low latency and real-time services <br> - The proposed scheme is not implemented via the blockchain platforms |
| 2019 | Sheikh et al. [36] | Internet of Energy | - Hash function | Byzantine based blockchain consensus | - Energy demand requirements with and without false data | + The success probability of an attack reduced using Byzantine-based blockchain consensus <br> - Data reliability and Non-repudiation are not considred |
| 2018 | Leng et al. [42] | Green IoT-based Agriculture | - Ellipse curve cryptography <br> - Hash function | Proof of stake consensus algorithm | - Average optimal cost of demand nodes | + Security and transparency of transaction data <br> - No analysis about resistant to attacks |
| 2018 | Jo et al. [47] | IoT-based healthcare | - SHA-256 hash function | PoW consensus mechanism | - Average throughput <br> - Block size against transactions/s | + Provide the authenticated and immutable records <br> - The effectiveness of the PoW consensus is a major issue |
| 2018 | Lin et al. [86] | Industry 4.0 | - Attribute-based signatures <br> - Multi-receivers encryption <br> - Hash function | PBFT consensus algorithm | - Time cost (s) | + Perfect forward secrecy <br> - Sybil attack is not considered |

*5) Blockchain storage size:* Hîrțan et al. [87] analysis the blockchain storage size by assuming an range of 0 to 1,000,000 blocks. The results show that for a quantity of 1,000,000 blocks, a 564 MB storage space is requested. Zhang et al. [54] computed the storage overhead for the initial settings file and the session and attributes, which the results show that it takes about 1104 bytes to store session keys where there are 10 requests.

*6) Blockchain update time overhead (ms):* Li et al. [32] analyzed the Blockchain update time overhead in the internet of vehicles, in which the results show that the block update time is increased if the sliding window is too small. Note that the UAV nodes utilize a sliding window to store recently updated blocks.

*7) Research questions-based metrics:* Chen et al. [88] study the performance evaluation of their scheme by defining the following six research questions: (a) Does the proposed scheme scale well for blockchain-based data trading? (b) Does the proposed scheme perform well in different data transmission losses? (c) How much can the proposed scheme follow the law
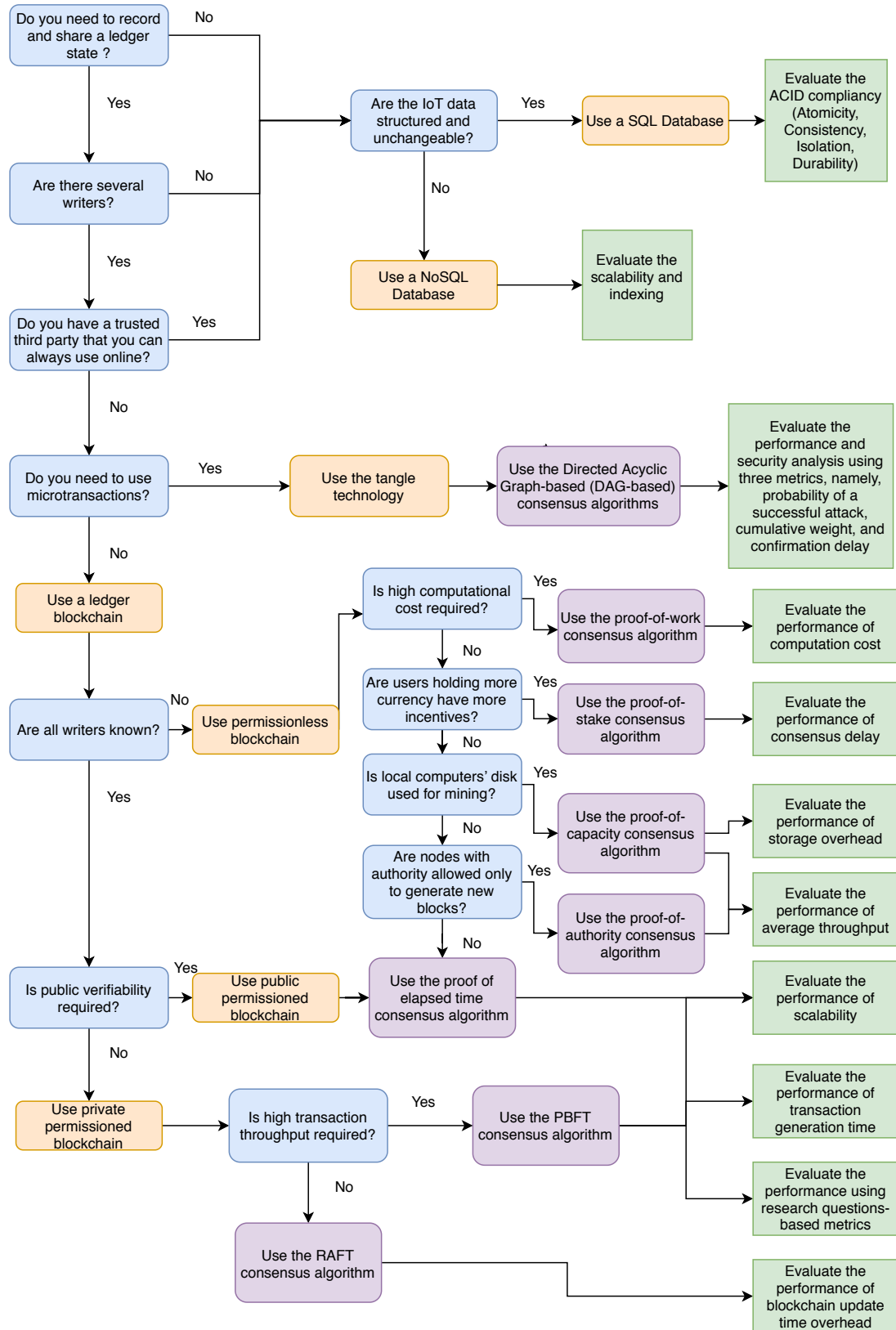
Fig. 10: A flowchart to determine whether Performance Metrics are appropriate to evaluate the performance evaluation of blockchain-based security and privacy systems.

of the market? (d) How can the proposed scheme encourage buyers and sellers to trade data? (e) How much benefit can the brokers gain in the proposed scheme? and (f) How can the proposed social welfare function converge?. The experimental results under 100 independent trials show that the proposed scheme can perform in different data transmission loss, encourage the buyers and sellers to participate in data trading as well as achieving the maximum social welfare.

*8) Impact of blockchain consensus rate:* The charge rate of proof-of-work in euro/kWh is evaluated by Dang et al. [89], which is an significant and important by-product of blockchain technology. The results show that the cost of proof-of-work is directly related to the amount of electricity purchased from the day-ahead, adjustment and balancing markets.

*9) Average throughput (requests per second):* Danish et al. [90] used the achieved throughput at the join server connected to the blockchain network as a performance metric in the conducted experiments. This performance metric is featured as a function of the number of join request messages per customer, for a different number of concurrent customers.

*10) Scalability of blockchain deployment service:* Consist to measure the deployment time of blockchain with various numbers of nodes. Lu et al. [91] evaluated the scalability of blockchain deployment service by setting the blockchain type as Ethereum and filling in the nodes' IP addresses for deployment. The good scalability is achieved when the deployment time increases in an approximately linear manner.

*11) Transaction generation time (ms):* Consist to measure the time of generating a transaction in the blockchain-based system. Shen et al. [92] use the transaction generation time as a performance metric to evaluate the performance of a blockchain-based system for medical image retrieval. Specifically, the transaction structure consisting of three parts, including, time information, retrieval information, and transaction information.

To ease the decision-making process on whether performance metrics are appropriate to evaluate the performance evaluation of blockchain-based security and privacy systems for the IoT networks, we provide a flow chart in Fig. 10.

### B. Blockchain Datasets

The blockchain datasets used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks are based on the search engines of the crypto space, named Blockchain explorers. Specifically, they are similar to an internet search engine, which can be used to view wallet details, blockchain transactions, and blocks...etc.

*1) Blockchain explorer [93]:* enables users to tag Bitcoin addresses with tags indicating the known Bitcoin address identities. The Blockchain explorer can be used to analyze Ethereum or Bitcoin Cash.Chang and Svetinovic [115] uses Blockchain explorer to identifies 2509 Bitcoin addresses which belong to 515 entities. Wang et al. [116] uses Bitcoin blockchain to collect transactions from January 3, 2009 (the genesis block) to June 30, 2017 (block 473,592), which they observe that about 0.48% of transactions still involve the vulnerability "ECDSA weak randomness" and that 1331 private keys are affected.

*2) Blockseer [94]:* offers the same functionality with Blockchain explorer and displays the connections among addresses and clusters addresses sharing the same label.

*3) Etherchain [95]:* is an Ethereum Blockchain Explorer contains every ether transaction made prior to the present date, which can be extracted for the price prediction experiment. Every element of a record contain a timestamp, beneficiary incentive in Ripple (XRP), sender, and exchange id. Poongodi et al. [117] uses Etherchain for evaluating the price prediction of the Ethereum blockchain cryptocurrency.

### C. Cryptography library

Tab. IV presents cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

- **Elliptic curve library :** Cheng et al. [81] use the elliptic curve library to evaluate the performance of semi-centralized traffic signal control mode with attribute-based blockchain. The following libraries are used on Java Runtime Environment 1.8 to construct bilinear pairs : libbswabe-0.9, ibrary bcprov-jdk15on-158, jpbc-plaf-1.2.1, jpbc-api-1.2.1, and commons-codec1.7. To encrypt/decrypt and sign/verify all messages generated, Luo et al. [70] uses the following two types of elliptic curves cryptography: ECC-secp256k1 and ECDSA-secp256k1, which are implemented in JAVA language.

- **MIRACL library [83]:** is Multiprecision Integer and Rational Arithmetic Cryptographic Library, which is used for elliptic curve cryptography.The MIRACL library is used by Ali et al. [82] for computing the execution time of the cryptographic operation underlying pairing-based cryptography. Niu et al. [55] used the Miracl library to implement cryptographic operations in order to evaluate the performance of blockchain-based key aggregation searchable encryption. Zhang et al. [72] used MIRACL for evaluating the performance of linkable group signature in IoT-based cryptocurrency. Li et al. [85] used MIRACL library to analyze the computational cost of the traceability for a privacy and regulation scheme in blockchain-based cryptocurrencies.

- **PBC (Pairing-Based Cryptography) library [78]:** is used by Eltayieb et al. [77] for evaluating the characteristics of the computational complexity of the concept of attribute-based signcryption with blockchain. The PBC is a free C library which executes the fundamental mathematical processes involved in pairing-based encryption systems.

- **Crypto++ Library [80]:** is a free C++ class library of cryptographic schemes. The library contains many algorithms, such as, authenticated encryption schemes (e.g., ChaCha20Poly1305 and XChaCha20Poly1305), high-speed stream ciphers (e.g., Panama, Rabbit (128/256)), message authentication codes (e.g., HMAC), hash functions (e.g., SHA-1 and SHA-2), and elliptic curve cryptography (e.g., ECDSA)...etc. Nkenyereye et al. [79] uses Crypto ++ library to evaluate the characteristics of computation and communication overhead of a secure and blockchain-based scheme.

TABLE VI: Testbeds used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

| Year | Scheme | Testbeds | Type | IoT applications | Focus of this work in the performance evaluation |
|---|---|---|---|---|---|
| 2020 | Ma et al. [109] | Ganache [118] | Private Ethereum network | Data crowdsourcing | - Evaluate the costs of smart contracts and for running data trade |
| 2020 | Liu and Zhang [110] | MATLAB environment [119] | Experimental environment | IoT data storage | - Evaluate the encryption speed of ECC in the blockchain network |
| 2020 | Zhang et al. [54] | Hyperledger Caliper [120] | Hyperledger group | Internet of Sensors | - Measuring the performance of blockchain-based collaborative access control scheme |
| 2020 | Tanwar et al. [121] | Hyperledger Caliper [120] | Hyperledger group | IoT-based healthcare | - Measuring the performance of blockchain-based access control policy algorithm |
| 2020 | Khan et al. [122] | MultiChain [123] | Open source blockchain platform | Electronic voting | - Evaluating the blockchain network in terms of unauthorized and authorized access |
| 2020 | Zhu et al. [40] | Ethereum | Private Ethereum network | Cloud Computing | - Building a federated blockchain system |
| 2020 | Yazdinejad et al. [124] | FPGA | Experimental environment | IoT-based NFV/SDN | - Implement a blockchain-enabled packet parser architecture |
| 2020 | Kadadha et al. [125] | Solidity [126] | Private Ethereum network | Data crowdsourcing | - Develop the smart contracts for a blockchain-based crowdsensing system |
| 2020 | Wang et al. [127] | Ethereum environment | Private Ethereum network | Industrial Internet of Things | - Validate the applicability of a reputation module in IIoT |
| 2020 | Lin et al. [128] | JUICE platform [129] | Open source blockchain platform | Data crowdsourcing | - To demonstrate the feasibility of the secure and privacy-preserving blockchain-based crowdsourcing system |
| 2019 | Maw et al. [130] | Go-ethereum | Private Ethereum network | Industrial Internet of Things | - Implementation of an operational data security scheme |
| 2019 | Lai et al. [69] | MATLAB environment [119] | Experimental environment | Internet of Vehicles | - Evaluate the importance of reputational data on the credibility of the data |
| 2019 | Islam and Shin [35] | MATLAB environment [119] | Experimental environment | Internet of Drones | - Estimating the effects in mobile edge computing server |
| 2019 | Luo et al. [70] | Hyperleader | Hyperledger group | Internet of Vehicles | - Realize the interaction between the consortium blockchain data and the application layer |
| 2019 | Li et al. [32] | Hyperledger Fabric 2.0 | Hyperledger group | Internet of Drones | - Evaluate the Blockchainupdate time and storage overhead |
| 2019 | Kaynak et al. [131] | NEthereum [132] | Private Ethereum network | Cloud Computing | - Integrate Ethereum blockchain into .NET applications with dotnet core framework. |
| 2019 | Sharma et al. [133] | MATLAB environment [119] | Experimental environment | Internet of Drones | - Evaluate the reliability through the area spectral efficiency, probability of connectivity, epoch, flyby time, and packet-survivability |
| 2019 | Sheikh et al. [36] | IEEE 33 bus system | Experimental environment | Internet of Energy | - Evaluate energy demand requirements |
| 2019 | Lu et al. [91] | Ethereum 1.5.9-stable | Private Ethereum network | Cloud Computing | - Evaluate the scalability of blockchain deployment service |
| 2019 | Kurt et al. [38] | IEEE-14 bus power system | Experimental environment | Internet of Energy | - Evaluate the false data injection attacks against the sensor measurements |
| 2019 | Shen et al. [92] | Ethereum Geth | Private Ethereum network | IoT-based healthcare | - Evaluate the performance of a blockchain-based system for medical image retrieval |
| 2019 | Wang et al. [74] | MATLAB environment [119] | Experimental environment | Fog/Edge Computing | - Simulate the optimal resource contribution of the fog node |
| 2019 | Ferrag and Maglaras [39] | MultiChain [123] | Open source blockchain platform | Internet of Energy | - Evaluate the performance of blockchain-based energy network |
| 2019 | Kochovski et al. [104] | Rinkeby Ethereum testnet [134] | Private Ethereum network | Fog/Edge Computing | - Evaluate the performance of blockchain–based trust management system |
| 2019 | Di Silvestre et al. [135] | Tendermint [136] | Open source blockchain platform | Internet of Energy | - Validate the distributed energy system using a blockchain network |
| 2019 | Zhou et al. [112] | Golang | Open source programming language | IoT-based healthcare | - Implement a prototype of permissioned blockchain |
| 2019 | Zhang et al. [73] | Ethereum environment | Private Ethereum network | Fog/Edge Computing | - Demonstrate the impact of the smart contracts for mobile edge computing |
| 2019 | Dang et al. [89] | MATLAB environment [119] | Experimental environment | Internet of Energy | - Study the impact of proof-of-work charge rate on the total cost |
| 2019 | Huang et al. [52] | Truffle [137] | Private Ethereum network | Edge/Fog Computing | - Realize the smart contract functionality for the decentralized fog computing environment |
| 2019 | Gai et al. [107] | Ethereum Geth | Private Ethereum network | Internet of Energy | - Study the cost of the time required to pack data into the blockchain system |
| 2019 | Danish et al. [90] | Ethereum Geth | Private Ethereum network | Internet of Sensors | - Deploy the smart contract and run the private blockchain network |
| 2019 | Arena et al. [43] | Hyperledger Fabric [138] | Hyperledger group | Green IoT-based Agriculture | - Implementing the blockchain for the certification and the traceability of extra virgin olive oil |
| 2019 | Lin et al. [56] | JUICE platform [129] | Open source blockchain platform | Internet of Sensors | - Evaluate the utility of a blockchain-based secure mutual authentication system |
| 2019 | Shih et al. [44] | Remix - Ethereum IDE [139] | Private Ethereum network | Green IoT-based Agriculture | - Testing the smart contract code of Ethereum |
| 2019 | Derhab et al. [140] | MultiChain [123] | Open source blockchain platform | Industry 4.0 | - Implement a private blockchain for industrial IoT |
| 2019 | Dai et al. [141] | Ethereum environment | Private Ethereum network | IoT data storage | - Measure the total time required for a secure data trading ecosystem |
| 2018 | Jo et al. [47] | Ethereum Mist Browser | Private Ethereum network | IoT-based healthcare | - Evaluate the feasibility and performance of a blockchain-based distributed network |
| 2018 | Lin et al. [86] | JUICE platform [129] | Open source blockchain platform | Industry 4.0 | - Investigate the time cost of cryptographic algorithms used in a blockchain-based system |

## D. Blockchain Testbeds

Tab. VI presents the blockchain testbeds used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

*1) Private Ethereum network:* Ethereum is the most used development platform in the performance evaluation of blockchain-based security and privacy systems for the IoT networks.

- **Ganache [118]:** is a private Ethereum blockchain, which can be used to implement smart contracts, develop programs and run scripts and tests. The testbed is available both as a desktop application and as a command-line tool. The Ganache testbed is used by Ma et al. [109] as a blockchain testing platform to evaluate the costs of smart contracts and for running data trade.

- **Ethereum Geth [96]:** is a decentralized framework that manages smart contracts via the implementation of the Ethereum protocol. Danish et al. [90] uses a geth Ethereum client, which is a Go language implementation of the Ethereum protocol in order to deploy the smart contract and run the private blockchain network. The Ethereum Geth is used by Gai et al. [107] for evaluating the time cost for packing up data in the blockchain system. To evaluate the scalability of blockchain deployment service, Lu et al. [91] deployed the uBaaS platform on an Alibaba Cloud4 virtual machine with Ethereum 1.5.9-stable and Proof-of-Work (PoW) as a consensus algorithm. Zhang et al. [73] deployed smart contracts in the Ethereum environment in order to demonstrate the performance of the smart contracts on the blockchain for mobile edge computing, which the results show that the financial cost of the implementation of smart contracts on the Ethereum network is relatively low. Shen et al. [92] use Ethereum as a proof-of-concept platform and use Geth as the Ethereum client to evaluate the performance of a blockchain-based system for medical image retrieval.

- **NEthereum [132]:** integrate Ethereum blockchain into .NET applications. Kaynak et al. [131] used the NEthereum library in the Ethereum network to execute transactions using the C# language with dotnet core framework.

- **Rinkeby Ethereum testnet [134]:** is test network for developers to develop and to do testing for Ethereum, which is based on a Proof-of-Authority consensus. Kochovski et al. [104] use Rinkeby Ethereum testnet to evaluate the performance of the blockchain-based trust management system for fog computing. Note that there are other test networks for Ethereum, namely, Kovan, Ropsten, and Görli.

- **Truffle [137]:** is a development and test environment with an asset pipeline for Ethereum, which provides network management for deploying to several public and private networks. Huang et al. [52] used Truffle [137] to realize the smart contract functionality for the decentralized fog computing environment.

- **Remix - Ethereum IDE [139]:** is a browser-based compiler and IDE that allows users to debug transactions and build Ethereum contracts using the Solidity language. Shih et al. uses [44] Remix - Ethereum IDE to testing the smart contract code of Ethereum for the organic production and trading of vegetables with blockchain.

- **Ethereum Mist Browser:** is a web application layer that allows visualizing web-based user interfaces for all types of Ethereum decentralized applications. Jo et al. [47] use Mist Browser and Go-Ethereum to simulate and evaluate the feasibility and performance of a blockchain-based distributed network for IoT-based healthcare.

- **Solidity [126]:** is an object-oriented, high-level language for implementing smart contracts for Ethereum. Kadadha et al. [125] uses Solidity with Web3j [142] to create and compile the smart contracts constituting the blockchain-based crowdsensing framework.

*2) Experimental environment:*

- **MATLAB environment [119]:** is used by Liu and Zhang [110] for evaluating the encryption speed of ECC in the blockchain network. Specifically, 100 storage nodes are set up with the limited capacity of each node is 3 TB, and the information and storage channel is fixed at 1000 Mbit/s. Lai et al. [69] analyzed the impact of reputation values on data credibility for internet of vehicles using MATLAB simulation, which the value of services of the vehicle users and the unit cost of vehicle users are chosen uniformly at random. Islam and Shin [35] performed a simulation using MATLAB for estimating the effects of a Blockchain-based secure data acquisition scheme with the use of a mobile edge computing server. Sharma et al. [133] analyzed the neural-blockchain-based scheme using the numerically-defined system model in Matlab in order to evaluate the reliability through the area spectral efficiency, probability of connectivity, epoch, flyby time, and packet-survivability. Dang et al. [89] uses the platform of MATLAB with the help of YALMIP toolbox in order to study the impact of proof-of-work charge rate on the total cost. Wang et al. [74] uses MATLAB R2018b simulation software to simulate the optimal resource contribution of the fog node.

- **IEEE 33 bus system:** This system is used by Sheikh et al. [36] to evaluate secured energy trading based on Byzantine-based blockchain consensus. The IEEE 33 bus system consists of 33-nodes and 32 branches. The evaluation for highlighting the impact of blockchain is carried out in two parts, namely, a) securing different nodes of the system, b) Securing energy and information data exchange.

- **IEEE-14 bus power system:** This system is used by Kurt et al. [38] for evaluating the false data injection attacks against the sensor measurements under a distributed dynamic state estimation in the internet of energy.

- **PROMELA [143]:** is a specification language for asynchronous systems, which is based on three building blocks, namely, process, data object, and message channels. Ali et al. [106] evaluated a blockchain-based decentralized architecture in Simple PROMELA INterpreter (SPIN) model checker. Specifically, the model consists

of one "Blockchain" process with "idle", "delegation", "activation" and "on" states.

- **Field Programmable Gate Array (FPGA):** refers to an integrated circuit consisting of an array of programmable cells, which is renowned for its faster-processing speed, high flexibility, and low resource consumption. Yazdinejad et al. [124] use FPGA for the implementation of blockchain-enabled packet parser architecture in order to evaluate in terms of resource utilization and power consumption.

*3) Hyperledger group:* Hyperledger [97] is an open-source community, hosted by the Linux Foundation, which focuses on developing a suite of stable frameworks, tools, and libraries for the deployment of blockchains at the enterprise level. Moreover, Hyperledger enables a variety of enterprise blockchain technologies, including intelligent contract engines, client libraries, utility libraries, distributed ledger frameworks, GUIs, and sample applications. Luo et al. [70] employs Hyperledger to realize the interaction between the consortium blockchain data and the application layer. To design smart contract algorithms, Li et al. [32] use the Java SDK "fabric-sdk-java" with Hyperleader's ChainCode technology.

- **Distributed Ledgers:** There are six distributed ledger frameworks, namely, Hyperledger Besu [144], Hyperledger Burrow [145], Hyperledger Fabric [146], Hyperledger Indy [147], Hyperledger Iroha [148], and Hyperledger Sawtooth [149]. The Hyperledger Besu is used in both public and private permissioned network, which is designed to be enterprise-friendly with including several consensus algorithms such as PoW, and PoA. The Hyperledger Burrow can be used for private/consortium networks, which is based on smart contracts and BFT consensus via the Tendermint algorithm. For developing applications with a modular framework, the Hyperledger Fabric can be used, which allows modules, such as membership services and consensus. To choose a distributed ledger framework interoperable with other blockchains for providing digital identities, the Hyperledger Indy can be used, which provides libraries, tools, and reusable modules. The Hyperledger Iroha is designed for IoT projects that require distributed ledger technology with a role-based permission model, while the Hyperledger Sawtooth can be used for IoT projects that require consensus algorithm named Proof of Elapsed Time (PoET). Tanwar et al. [121] use Hyperledger Caliper [120] for measuring the performance of blockchain-based access control policy algorithms in IoT-based healthcare.
- **Libraries:** There are four libraries developed by Hyperledger group for distributed ledger frameworks, namely, Hyperledger Aries, Hyperledger Quilt, Hyperledger Transact, Hyperledger Ursa [150].
- **Tools:** There are five tools developed by Hyperledger group for distributed ledger frameworks, namely, Hyperledger Avalon [151], Hyperledger Caliper [120], Hyperledger Cello [152], Hyperledger Explorer [153], and Hyperledger Grid [154]. Zhang et al. [54] used Hyperledger Caliper [120] for measuring the performance of

blockchain-based collaborative access control scheme.

*4) Open source blockchain platforms:*

- **MultiChain [123]:** is a platform for establishing a private blocking chain that can be used by organizations for financial transactions. The MultiChain platform provides a simple API and command-line interface with the property to restrict access to the blockchain via a list of authorized users. In addition, the MultiChain platform is characterized by the scalability of selective stream indexing and the data management of real-time data feeds. Ferrag and Maglaras [39] created a private blockchain using MultiChain to evaluate the performance of blockchain-based energy networks.
- **Tendermint [136]:** Tendermint Core is Byzantine Fault Tolerant (BFT) middleware that takes a state transition machine and replicates it on many machines. Di Silvestre et al. [135] uses Tendermint 0.24 to validate the distributed energy system using a blockchain network.
- **JUICE platform [129]:** is an open permissioned blockchain service platform. This platform can support the design of smart contracts using Solidity and possess a Java and Javascript-based web/client tools for managing and monitoring. Lin et al. [56] uses the JUICE platform to evaluate the utility of a blockchain-based secure mutual authentication system. Lin et al. [86] uses the JUICE platform to investigate the time cost of cryptographic algorithms used in a blockchain-based system with fine-grained access control for industry 4.0 deployments.
- **Other blockchain platforms:** There are other open-source blockchain platforms that can be used as blockchain testbed for the performance evaluation of blockchain-based security and privacy systems. We cite the following ten blockchain platforms: Algorand, HydraChain, Stellar, Waves Platform, Tezos, Smilo, Quorum, NEM, Qtum, and Openchain.

## VI. Lessons Learned

Blockchain technology becomes the most popular communication platform in the development of the internet of things. The blockchain-based security and privacy systems have received a high level of scientific research attention in addressing the challenging issues of security and privacy in IoT networks. For this reason, we have examined the performance evaluation of blockchain-based security and privacy systems for the IoT networks from different perspectives, and we summarize the lessons learned from this review below.

From the security analysis techniques point of view, there are four basic techniques, namely, BAN logic, game theory, theory analysis, and AVISPA tool. These techniques can be used for analyzing the security theorems of blockchain-based security and privacy systems in terms of security requirements (e.g., traceability, identity privacy, Location privacy, non-repudiation, authentication,...etc), and resistance to attacks (e.g., replay attacks, quantum attacks,...etc).

Through in-depth analysis and research, we were able to classify the security and privacy requirements for blockchain-based IoT applications into integrity, authentication, non-repudiation, traceability, identity privacy, location privacy,

scalability, unforgeability, anonymity, trust management, access control, data reliability, perfect forward secrecy, confidentiality, and data auditability.

From the attacks of blockchain technologies vulnerability, we found nine-teen attacks discussed by the surveyed blockchain-based security and privacy systems, including, replay attack, man-in-the-middle attack, chosen message attack, denial of service attack, sybil attack, bad-mouthing attack, on-off attack, whitewashing attack, false data injection attack, impersonation attack, modification attack, physical capture attack, eavesdropping attack, collusion attack, anti-key-leakage attack, cross-pairing attack, keyword guessing attack, 51% attacks, and double spending.

Based on the performance metrics used in the performance evaluation of blockchain-based security and privacy systems for the IoT networks, we found eleven metrics, including, consensus delay, communication cost, computation cost, storage overhead, blockchain storage size, blockchain update time overhead, research questions-based metrics, impact of blockchain consensus rate, average throughput, scalability of blockchain, and transaction generation time.

According to the blockchain testbeds used in the performance evaluation of blockchain-based security and privacy systems, we were able to classify the blockchain testbed into private ethereum network, experimental environment, hyperledger group, and open source blockchain platforms. From the cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems, we found four cryptography libraries, including, elliptic curve library, pairing-based cryptography library, crypto++ library, and MIRACL library.

On the basis of the aforementioned studies and analyses that we have performed, we propose a thirteen-step process for building and evaluating a blockchain-based security and privacy system:

1) Configuration of the IoT network (e.g. Fog/Edge computing, SDN/NFV, Cloud computing,...etc.),
2) Selection of a consensus algorithm (e.g., proof-of-work, proof-of-stake,...etc),
3) Definition of the security and privacy requirements (e.g., integrity, authentication, non-repudiation, traceability,...etc.),
4) Definition of smart contracts to manage transactions under specific conditions,
5) Definition of the threat models (e.g., 51% attacks, denial of service attack, sybil attack, bad-mouthing attack,...etc.),
6) Identification of vulnerability and possible interdependencies of the blockchain-based security and privacy system,
7) Selection of the cryptographic methods (e.g., SHA-256 hash function, ellipse curve cryptography, ciphertext-policy attribute-based encryption...etc.),
8) Proposition of the principal steps of the blockchain-based security and privacy system (e.g. system initialization, device authentication, ...etc.) with considering the configuration of the IoT network,
9) Analyzing the robustness of the blockchain-based security and privacy system using different security analysis techniques (e.g., BAN logic, game theory, theory analysis, and AVISPA tool),
10) Selection of a cryptography library (e.g., elliptic curve library, pairing-based cryptography library, crypto++ library, MIRACL library,...etc.),
11) Selection of a blockchain explorer (e.g., Blockchain explorer, Blockseer , Etherchain, ...etc.),
12) Selection of a blockchain testbed (e.g., private ethereum network, experimental environment, hyperledger group, open source blockchain platform, ...etc.),
13) Evaluate the blockchain-based security and privacy system using different performance metrics (e.g., consensus delay, communication cost, computation cost, storage overhead, blockchain storage size, ...etc.).

## VII. Open challenges and future research opportunities

To complete our review, we outline both open challenges and future research opportunities that could improve the capabilities and effectiveness of blockchain-based security and privacy systems for the IoT networks, summarized in the following suggestions:

### A. Evaluating the blockchain-based intrusion detection systems

There is recent work that combines the intrusion detection systems with blockchain technology for the IoT networks [155]–[157]. The intrusion detection system is proposed to defend against the forged commands and detect network attacks using machine learning (e.g., deep learning), while the blockchain technology is proposed for checking the data integrity as well as enabling transparency of information. Therefore, when evaluating the performance of blockchain-based intrusion detection systems, it is struggling to find comprehensive and valid cyber security datasets [158]. Currently, the most cyber security datasets used in the performance evaluation of intrusion detection systems are not simulated on blockchain-based IoT environments, such as KDD Cup 1999 dataset, UNSW-NB15 dataset, and NSL-KDD dataset. The development of a new dataset to build a network intrusion detector under a blockchain-based IoT environment is one of the significant research challenges.

### B. Developing efficient consensus mechanisms

The most popular consensus algorithms used in the blockchain are PoW, PoS, and PBFT. These consensus algorithms does not take into consideration the capacity limits for storage and computing of IoT devices. The IOTA project [159] is a cryptocurrency for the IoT industry which enables micropayment transactions between IoT devices and protects the integrity and verifiability of data [160]. The IOTA adopts DAG consensus (i.e., no miners) which can achieve high throughput with low computational overhead [27]. Therefore, there are many characteristics that should be taken into consideration

when developing more efficient consensus mechanisms for IoT networks such as transaction processing rate, security service, quantum computations, and decentralized trust. A possible research direction in this topic could be related to developing a hybrid consensus mechanism that combines the advantages of both DAG and other consensus algorithms. In addition, we believe that performance and security analysis of resistance to quantum computations is needed for the IOTA project.

### C. Blockchain-based software-defined networking for IoT application

We have seen that the combination of blockchain technology and software-defined networking offers promising opportunities to address the security challenges of the IoT environment and make it more secure. However, several challenges remain for the practical realization of the blockchain-based software-defined networking to replace the existing schemes. The absence of strong cryptographic encryption schemes between the SDN controller and the blockchain database can result in a serious violation of the confidentiality of communications [161]. Hence, autonomous trust mechanisms for establishing the authenticity of communication between the SDN controller and the blockchain database must be designed and implemented. In addition, the issue of man-in-the-middle attacks and denial of service attacks against the blockchain-based software-defined networking for IoT application still remains a very challenging one to tackle.

### D. 5G-enabled blockchain-based IoT networks

Since the information on the state and location of an IoT node contained in the broadcast messages could be captured and used for misuse, the privacy leakage risk of blockchain will be more significant in 5G-enabled blockchain-based IoT networks. The technique for hiding the true identity of an IoT device is anonymity, which can be ensured by pseudonyms. Therefore, any person, organization, industry, public sector, or even attacker can access the detailed tracking information of IoT devices (e.g., vehicles) by reviewing the messages broadcasted periodically by IoT devices [162]. Some interesting technologies can be applied to this problem: game theory and reinforcement learning [163], privacy-aware and asynchronous deep learning [164], and privacy-preserving range query [164]. Hence, conducting researches and developing more secure, efficient, and practical privacy-preserving schemes using these technologies for 5G-enabled blockchain-based IoT networks will contribute significantly to the development of blockchain.

### E. Secure blockchain ledgers at Fog computing

Caching the blockchain ledgers at the storage spaces on Fog computing is an efficient and cost-effective approach to reducing the latency of IoT-enabled blockchain [165] as well as traffic overhead in large-scale industrial applications [166]. The confidentiality of blockchain ledgers, however, is difficult to preserve, from which attackers can deduce transactions from target IoT devices. To secure blockchain ledgers at fog computing, the following critical challenges need to be solved

[167]: a) How to select trusted nodes at fog computing for caching blockchain ledgers?, b) When IoT devices request the blockchain ledgers, where cache the requested IoT data?, and c) When trusted nodes at fog computing are damaged, how to ensure the confidentiality of blockchain ledgers?. Some interesting cache placement strategies can be applied to this problem: privacy-preserving data aggregation [168], enhanced revocable access control [169], fog data dissemination [170], and privacy-preserving range query [171]. Thus, conducting researches on blockchain ledgers replacement approaches and developing more secure, efficient, and practical data retrieval schemes will contribute significantly to the development of secure blockchain ledgers at Fog computing.

### F. Developing efficient and privacy-preserving schemes

The IoT devices in blockchain-based IoT applications have group-based behavior and high/frequent mobility that require new challenges in privacy-preserving. However, some emerging cryptographic techniques, e.g. anonymization, mixing, and differential privacy, etc., can be considered to design an efficient and privacy-preserving scheme. The anonymization techniques such as k-anonymity aim to hide the querying user among k users [172]. The differential privacy techniques aim to protect real-time data by adding random noise based on the mathematical algorithms, e.g., Laplace distribution, Symmetric geometric distribution, etc [173], while mixing technique is used to improve anonymity by mixing tokens [174]. To design efficient and privacy-preserving schemes using these techniques, the following critical challenges need to be solved:a) How to optimize the computing cost for k-anonymity mechanisms since the IoT devices are characterized by limited resources?, b) How to add appropriate noises to support differential privacy?, and c) How to achieve a good trade-off of efficiency, accuracy, and privacy?. To this end, these cryptographic techniques should be carefully designed to provide efficient and privacy-preserving schemes for blockchain-based IoT applications.

## VIII. Conclusion

In this paper, we surveyed research challenges and a tutorial on performance evaluation of blockchain-based security and privacy systems for the IoT networks. We reviewed the blockchain-based security and privacy systems for seventeen types of IoT applications, e.g., Industry 4.0, Software Defined Networking, Edge computing, Internet of Drones, Internet of Cloud, Internet of Energy, Internet of Vehicles, etc. We also reviewed various consensus algorithms and provide a comparison with respect to the nine properties such as latency, throughput, computation, storage, and communication costs, scalability, attack model, advantage, and disadvantage...etc. Through in-depth analysis and research, we were able to classify the security analysis techniques and provide a classification into four categories, including BAN logic, game theory, theory analysis, and AVISPA tool. Furthermore, we analyzed the performance metrics, blockchain testbeds, and cryptography libraries used in the performance evaluation of blockchain-based security and privacy systems for the IoT

networks. On the basis of the current survey, we discussed the major steps to follow for building and evaluating blockchain-based security and privacy systems. Lastly, we discussed and highlighted open challenges and future research opportunities.

## ACKNOWLEDGEMENT

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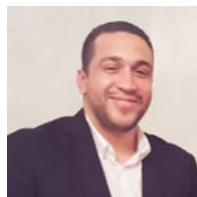
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