



BLOCKCHAIN FOR INTERNET OF THINGS: A SURVEY

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Abstract: The Internet of Things (IoT) is transforming the established sector into a smart one that uses data to inform decisions. However, intrinsic features of IoT result in a number of challenges, such as decentralization, inadequate interoperability, privacy, and security vulnerabilities. Blockchain technology provides the opportunities in addressing the challenges of IoT. In this paper, we investigate the incorporation of blockchain technology with IoT. We name such synthesis of blockchain and IoT as blockchain of things (BCoT). This paper presents an in-depth survey of BCoT and discusses the insights of this new paradigm. In particular, we first briefly introduce IoT and discuss the challenges of IoT. Then, we deliver an overview of blockchain technology. We next concentrate on introducing the convergence of blockchain and IoT and presenting the proposal of BCoT architecture. We further discuss the issues about using blockchain for fifth generation beyond in IoT as well as industrial applications of BCoT. Finally, we outline the open research directions in this promising domain.

Keywords – IOT, Blockchain.

I. INTRODUCTION

The latest breakthroughs in information and communication technology (ICT) have promoted the evolution of traditional smart industry with data-driven decision making, as opposed to computer-aided industry [1]. The Internet of Things (IoT) plays a crucial role in this paradigm shift by establishing a cyber- physical system (CPS) by linking the physical industrial environment to the cyberspace of computer systems. IoT may serve a vast variety of industrial applications, such as manufacturing, logistics, culinary industry, and utilities. IoT aims to increase operation efficiency and production throughput, minimize the machine outage and boost product quality.

In particular, IoT has the following features:

- Decentralization of IoT systems
- Variety of IoT devices and systems
- Heterogeneity of IoT data
- Network complexity

All of them result in the issues including heterogeneity of IoT system, inadequate interoperability, resource restrictions of IoT devices, and privacy and security vulnerabilities. The introduction of blockchain technologies brings the opportunity in solving the above issues of IoT. A blockchain is fundamentally a distributed ledger extending over the complete consensus, blockchains can enable a transaction to occur and be validated in a mutually distributed system without the involvement of the trusted third party. Unlike traditional transaction management systems where the centralized agency has to verify the transaction, blockchains may achieve the decentralized validation of transactions, hence significantly saving the cost and easing the performance bottleneck at the central agency. Moreover, each transaction saved in blockchains is essentially immutable as each node in the network preserves all the committed transactions in the blockchain. Meanwhile, cryptographic mechanisms (such as asymmetric encryption algorithms, digital signature, and hash functions) maintain the integrity of data blocks in the blockchains. Therefore, the blockchains can provide nonrepudiation of transactions. In addition, each transaction in blockchains is traceable to every user with the affixed historic timestamp.

Blockchain is fundamentally a great complement to IoT with the better interoperability, privacy, security, dependability, and scalability. In this work, we study a novel paradigm of integrating blockchain with IoT. We describe such synthesis of blockchain with IoT as blockchain of things (BCoT).

In Specifically, BCoT has the following benefits.

- Interoperability among IoT devices, IoT systems and industrial sectors, where the interoperability is the capacity of interacting with physical systems and exchanging information across IoT systems. It can be done via the blockchain-composite layer established on top of an overlay peer-to-peer (P2P) network with universal access across diverse IoT systems.
- The capacity to track and validate the temporal and geographical details of a data block recorded in the blockchain is known as traceability of IoT data. Each data block saved in a blockchain is affixed with a historic timestamp consequently insuring the data traceability.
- Reliability of IoT data is the quality of IoT data being trustworthy. It may be assured by the integrity imposed by cryptographic mechanisms like asymmetric encryption algorithms, hash functions and digital signature, all of which are inherent in blockchains.
- The term "autonomic interactions" describes an Internet of Things system's capacity to communicate with itself without the need of a reliable third party. This autonomy may be accomplished using smart contracts provided by blockchains. In example, contract clauses imbedded in smart contracts will be implemented automatically when a certain condition is achieved (e.g., the user breaching the contract would be penalised with a fine automatically).

II. Internet of Things

Today's industry is experiencing a paradigm transition from conventional computer-aided industry to smart industry driven by recently advancements in IoT and big data analytics (BDA). During this evolution, IoT plays a critical role of bridging the divide between the physical industrial environment and the cyberspace of computing systems while BDA can help to extract concealed values from enormous IoT data so as to make intelligent decisions.

IoT is fundamentally a network of smart objects (i.e., things) with provision of various industrial services. A typical IoT system consists of the following layered subsystems (from bottom to up) as shown in Fig. 1.

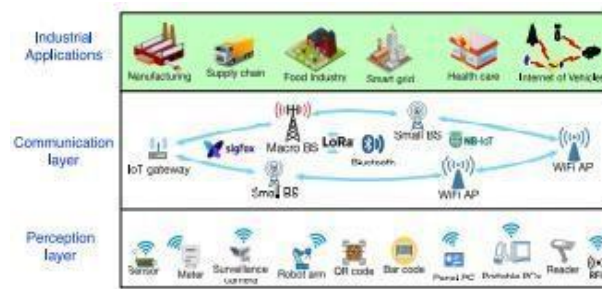


Fig. 1. IoT consists of perception layer, communication layer, and industrial applications [2]

- **Perception Layer:** The range of Internet of Things devices is extensive and includes sensors, actuators, controllers, bar code/quick response code (QR code) tags, RFID tags, smart meters, and other wireless/wired devices. These devices can detect and capture data from the physical environment. Meanwhile, some of them (such as actuators and controllers) can make activities on the surroundings.
- **Communication Layer:** To create an industrial network, a variety of wired and wireless devices, including sensors, RFIDs, actuators, controllers, and other markers, may connect to WiFi access points (APs), IoT gateways, small base stations (BSs), and macro BSs. The network connection is enabled by a diverse of communication protocols, such as Bluetooth, near field communications (NFCs), low-power wireless personal area networks (6LoWPANs), wireless highway addressable remote transducer (WirelessHART) [10], low power wide area networks (LPWANs) technologies including Sigfox, LoRa, narrowband IoT (NB-IoT), and industrial Ethernet [3].
- **Industrial Applications:** IoT may be widely employed to support a range of industrial applications. The typical industrial uses include manufacturing, supply chain, gastronomic healthcare, smart infrastructure, industry, and the Internet of Vehicles (IoV).

Challenges in Internet of Things: Our primary emphasis in this research is industrial IoT. Without losing generality, we now refer to Industrial IoT as IoT. With the use of different electrical or mechanical sensors, actuators, and software systems that can detect and gather data from the physical world and then take appropriate action, the Internet of Things (IoT) makes it possible for a variety of things (smart items) to be connected. The following are some of the research problems that the IoT's unique characteristics provide.

- IoT systems are diverse, as seen by the variety of IoT devices, communication protocols, and data kinds (structured, semi-structured, and unstructured). Other issues like interoperability, privacy, and security (which will be discussed below) are also caused by heterogeneity.
- Network complexity in the Internet of Things, many network and communication protocols coexist. NFC, Bluetooth, 6LoWPAN, WirelessHART, Sigfox, LoRa, and NB-IoT are examples of common network protocols that provide various network services. For instance, LPWAN technologies may have coverage ranging from 1 to 10 km, but 6LoWPAN and WirelessHART technologies often have limited communication coverage (less than 100 m) [4].

- The ability of IoT systems (hardware and software) to communicate, use data, and work together is known as poor interoperability. Data communication across various industrial sectors, strategic centres, and IoT systems is difficult because of the decentralisation and heterogeneity of IoT systems. Consequently, it is challenging to accomplish IoT interoperability.
- IoT devices resource constraints including sensors, actuators, RFID tags, and smart meters, have limited computational, storage, and battery power resources. For instance, passive RFID tags that can only collect energy from RFID readers or the surrounding environment lack a battery [5]. Furthermore, IoT devices are susceptible to malicious assaults as a consequence of resource limitations.
- Privacy Vulnerability it ensures that IoT data is used appropriately and that no user private information is disclosed without authorisation. Because of the complexity, decentralisation, and heterogeneity of IoT systems, protecting data privacy in this context is difficult. Furthermore, as cloud computing may provide IoT additional processing and storage capability, integrating IoT with cloud computing is becoming popular. Nevertheless, sending private IoT data to external cloud services might jeopardise the IoT's already precarious privacy [6].
- Security vulnerability although it is crucial for a company, the decentralization and heterogeneity of IoT systems can make it challenging to guarantee IoT security. Since it might be challenging to deploy security countermeasures in resource-constrained IoT systems, conventional methods like authentication, authorization, and communication encryption might not be suitable for IoT. Furthermore, the inability to update security firmware on time makes IoT devices susceptible to malevolent assaults [7].

III. Blockchain Technologies

Overview of Blockchain Technologies

In essence, a blockchain is a distributed ledger that spans the whole blockchain system [8]. An example blockchain with many sequentially linked blocks is seen in Fig. 2. With the exception of the initial block, every block in a blockchain references the block that came just before it, known as the parent block, using an inverse reference that is basically the parent block's hash value. For instance, as shown in Fig. 2, block i includes the hash of block $i - 1$. A blockchain's genesis block, which has no parent block, is its first block. Specifically, a block structure has the following data:

- Block version (which indicates the validation rules to be followed)
- Parent block hash Timestamp, which records the current time in seconds
- Nonce, which starts at 0 and increases for each hash calculation
- Transaction count MerkleRoot, which is the hash value of a Merkle tree's root after concatenating the hash values of all the transactions in the block, as illustrated in Fig. 2's detailed view. As transactions are carried out, a blockchain keeps expanding.

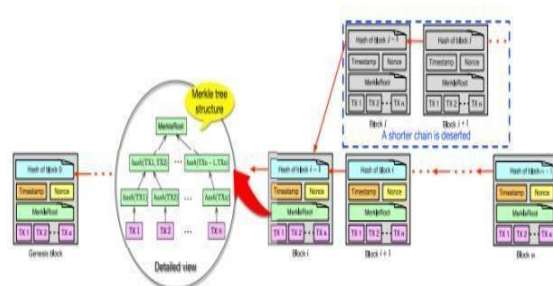


Fig. 2. Blockchain consists of a number of consecutively connected blocks and the detailed view represents a Merkle tree structure (where TX represents a transaction) [9]

Every node in the network will take part in the block validation process whenever a new block is created. The inverse reference pointing to the parent block will automatically add a verified block to the end of the blockchain. Because the hash value of the tampered block differs greatly from that of the original block, any unauthorised changes to the previously created block may be quickly identified in this way. Furthermore, other nodes in the network may readily notice the meddling behaviour since the blockchain is dispersed across the whole network.

Blockchain data integrity guarantee: Blockchains use cryptographic methods to ensure data integrity. Specifically, blockchains use two approaches to guarantee data integrity.

- An ordered link list structure of blocks where the hash value of the previous block must be included in every newly added block. This way, if any of the earlier blocks are falsified, the later blocks will be deemed invalid.
- The Merkle tree structure, where a root hash of a Merkle tree of all the transactions is included in every block. In essence, each nonleave node is a hash value of the two values of its two offspring concatenated. As a result, a Merkle tree is usually binary. In this manner, any transactional falsification will result in a new hash value in the layer above, which will then produce a false root hash. Any fabrication may thus be quickly identified.
- Consensus Algorithms: One benefit of blockchain technology is their ability to verify the trustworthiness of blocks in a decentralised, trustless setting without requiring the involvement of a reliable third party. It is difficult to come to an agreement on a freshly created block in a distributed setting as the consensus might be skewed in favour of rogue nodes.

Consensus methods may be used to validate trustworthiness in a decentralised setting. Proof of work (PoW), proof of stake (PoS), and practical Byzantine fault tolerance (PBFT) are examples of common consensus methods [10]. Consider PoW as an illustration. Solving a computationally challenging task is similar to creating a freshly created block. This is computationally malicious nodes. Even a challenging issue, often referred to as a puzzle, may be easily verified [11]. In the distributed P2P network, every node is able to take part in the validation process. The first node, commonly known as a miner, to solve the problem may add the verified block to the blockchain. Other nodes then validate and update the new findings in the blockchain once it broadcasts the validation results across the whole blockchain system. This node will thereafter get a little bonus as payment for resolving the challenge.

- **Resolution of discrepancies:** Several nodes may verify blocks almost simultaneously in a distributed system. At the same time, bifurcated (or forked) chains may be the consequence of network slowness. Since the longest chain suggests the greatest tolerance for being compromised by attackers, the majority of current blockchain systems usually keep the longest chain as the legitimate chain in order to resolve the disparity. If this is the case, the longest chain will continue to be validated in the future, and a shorter chain—the blue dashed-line box in Figure 2—is automatically abandoned.
- **PoW's Trustworthiness:** PoW's trustworthiness is predicated on the notion that the vast majority of blockchain nodes are reliable. In general, 51% of processing power is thought to be the point at which PoW can withstand malicious assaults. Miners may be encouraged to be truthful rather than compromise via the incentive systems. Meanwhile, it usually takes a lot of processing power to solve the problem. The likelihood that a miner would solve the riddle is often correlated with their processing power and resources [12]. PoW strategies use a lot of energy since they need to do a lot of computation to solve the problem. Because users with more cryptocurrency (i.e., more stakes) are more trustworthy than those with less, PoS, in contrast to PoW, needs evidence of ownership to verify the legitimacy of a block. Every node in PBFT that has an equal chance of casting a vote for the consensus will communicate its voting status to other nodes. Following many vote rounds, an agreement is reached.

Typical consensus algorithms may be broadly divided into two categories: There are two types of consensus algorithms:

- Probabilistic
- Deterministic

The taxonomy is provided in Table I. Deterministic consensus algorithms first consent to the block before saving the validated block to the chain, whereas probabilistic consensus algorithms, such as PoW, PoS, and delegated POS (DPOS), usually save the validated block to the chain first and then look for consensus from every node. Furthermore, probabilistic consensus techniques often produce many bifurcate chains; the longest chain is selected to resolve the dispute.

Deterministic consensus algorithms, on the other hand, resolve the disparity by use of many iterations of overlay network communications. Numerous initiatives, including Ripple [13], Algorand [14], Tendermint, proof of authority (PoA) [15], and proof of elapsed time (PoET) [16], are aimed at enhancing the established consensus algorithms. To meet the needs of various applications, there is a tendency towards combining many consensus algorithms rather than selecting just one. How Blockchains Operate: Next, we provide an illustration of how a blockchain functions. Consider the example of a money transfer in Fig. Alice wishes to send Bob a certain sum of money. She starts the transaction by using her Bitcoin (BTC) wallet on a computer (step 1). Information like the sender's wallet, the recipient's address, and the total amount of money are all included in the transaction. Alice's private key effectively signs the transaction, and other users may then access and validate it using Alice's public key. The computer then advertises the started transaction to other P2P network nodes, or computers (step 2). A verified transaction is subsequently attached to Fig. 3, which shows the blockchain's operational flow. When a miner successfully completes the puzzle (i.e., step 3), they go to the end of the chain of transactions, therefore creating a new block on the blockchain. Lastly, after the verified transaction is added to the blockchain (step 4), each node keeps a copy of the revised blockchain.

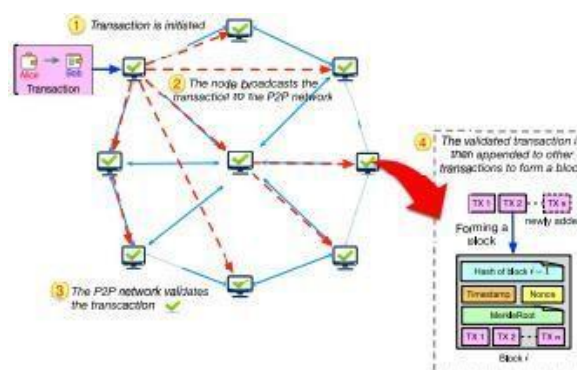


Fig. 3. Working flow of blockchains [17]

Key Characteristics of Blockchain

In summary, blockchain technologies have the following key characteristics.

- **Decentralisation:** Transaction validation in conventional transaction management systems has been carried out via a reliable organisation (such as the government or a bank). At centralised service providers, this centralisation approach always leads to increased expenses, performance snags, and single-point failures (SPF). Block chain, on the other hand, enables transactions to be verified between two peers without the need for central agency authentication, jurisdiction, or intervention. This lowers the risk of SPF, lowers service costs, and mitigates performance bottlenecks.

- **Immutability:** A block chain is made up of a series of blocks that are connected one after the other, with each link basically representing the inverse hash point of the block before it. Any changes made to the preceding block render all blocks that follow invalid. In the meanwhile, the hash of every transaction that has been committed is saved in the root hash of the Merkle tree. Every transaction, no matter how little, creates a new Merkle root. Any fabrication may thus be quickly identified. Data integrity may be ensured by combining the Merkle tree with the inverse hash point.
- **Non-repudiation:** Keep in mind that the transaction is signed using the private key, which enables others to view and validate it using the matching public key. As a result, the transaction initiator cannot reject the transaction that has been cryptographically signed.
- **Transparency:** Every user has an equal right to access and engage with the blockchain network on the majority of public blockchain systems, such as Bitcoin and Ethereum. Additionally, each new transaction is verified and recorded on the blockchain, making it accessible to all users. As a result, any user who has access to the blockchain and is able to confirm the transactions that have been committed may see the data on the blockchain.
- **Pseudonymity:** Blockchain systems may maintain a certain degree of privacy by keeping blockchain addresses anonymous, even while blockchain data is transparent. For instance, the work of [18] offers a blockchain application to protect personal data privacy. However, since blockchain addresses are basically traceable by inference, blockchain can only protect privacy to a limited extent [19]. For instance, [20] demonstrates how blockchain data analysis may be used to identify fraudulent activity and illicit transactions. As a result, blockchain can only maintain pseudonymity rather than complete privacy.
- **Traceability:** A timestamp, which is noted at the moment the transaction takes place, is appended to every transaction stored in the blockchain. Thus, after examining the blockchain data with matching timestamps, users may quickly confirm and track the provenance of previous data items.

Convergence of Blockchain

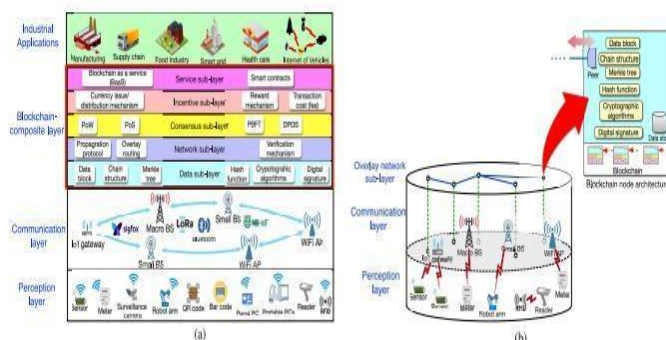
- **Opportunities of Integrating Blockchain With IoT:** Integrating blockchain with IoT, termed BCoT, offers several advantages that address key IoT challenges such as system heterogeneity, poor interoperability, resource constraints, and security vulnerabilities. Enhanced Interoperability: Blockchain improves IoT interoperability by converting diverse IoT data types into blockchain-compatible formats, making it easier to operate across fragmented networks using P2P overlay networks.
- **Improved Security:** Blockchain secures IoT data by storing it as encrypted, digitally signed transactions, reducing vulnerability to breaches. Smart contracts also enable automatic updates of device firmware, enhancing system security.
- **Traceability and Reliability:** Blockchain's immutable ledger allows for real-time data verification and tracking. Applications such as product traceability benefit from this, since the Product quality and provenance may be confirmed, guaranteeing the accuracy of the data. Self-governing IoT Communication: Blockchain enables distributed autonomous corporations (DACs) to communicate with IoT devices autonomously using smart contracts, lowering operating costs and requiring less human intervention. All things considered, BCoT improves data traceability, security, interoperability, and autonomous operations, strengthening the resilience and effectiveness of IoT systems.

IV. Architecture of Blockchain

We suggest the BCoT design seen in Figure 4. The blockchain-composite layer in this architecture serves as a mediator between industrial and Internet of Things applications. Two advantages of this approach are that it 1) provides an abstraction from the IoT's lower levels and 2) offers blockchain-based services to users. Specifically, the heterogeneity of lower levels (such as the IoT's sensing and communication layers) is concealed by the blockchain-composite layer. However, in order to enable a variety of industrial applications, the blockchain-composite layer offers a number of blockchain-based services, which are effectively application programming interfaces (APIs). As a result, the abstraction achieved by the blockchain-composite layer may help lessen the burden of creating industrial applications. As seen in Fig. 4(a), the blockchain-composite layer is made up of five sublayers, arranged from bottom to top.

- **Data Sublayer:** Gathers IoT data from lower layers (perception layer, for example) and uses hash functions and asymmetric cryptographic methods to wrap up the encrypted data with a digital signature. Following the distributed validation, these successively linked data blocks make up the blockchain. Various blockchain systems may choose distinct hash functions and cryptography methods. For instance, the Bitcoin blockchain uses ECDSA as the signature method and SHA-256 as the hash function.
- **Network Sublayer:** Functioning on top of the communication layer, it is basically an overlay P2P network. The nodes of the underlying communication networks—that is, wired and wireless networks—are connected by either virtual or physical links to form the overlay network. A single node only forwards the transaction block to its peers that are linked to it. Other peers will locally validate the transaction block when it has been received. The block will spread to further nodes via the overlay network if it is legitimate.
- **Consensus Sublayer:** Its main function is to facilitate distributed consensus over a block's reliability. Many consensus algorithms, including PoW, PoS, PBFT, and DPOS (described in Section III-A2), may reach the consensus. It is important to note that distributed consensus algorithms need block propagation techniques, such as relay network propagation and advertisement-based propagation [20].

- It is important to note that, as seen in Fig.4(b), the network sublayer that is built on top of the communication layer is the abstraction of networks underneath communication networks, therefore providing a universal network access across different networks. The architecture of a blockchain node, which basically consists of blockchain data and other components in the data sublayer, is also shown in Fig.4(b).



V. Applications

- **Food Sector:** BCoT may increase the product life cycle's visibility, especially in the food industry. To ensure food safety, food products' traceability is very important. Nonetheless, it is challenging for the current IoT to guarantee food traceability along the whole food supply chain [21]. A food company, for instance, can have a large number of suppliers. Digitising raw material data from its source to each stage of food production is necessary for traceability. Blockchain technology can guarantee the authenticity and traceability of food sector data throughout this process. This aspect contains a variety of concepts. For instance, the study by [22] suggests combining blockchain technology with RFID to build a supply chain network that connects China's food and agriculture industries. Data from the food supply chain may be traced thanks to this technology. In the meanwhile, according to the research by [23], blockchain technology might improve food safety by supplying traceable food goods. Furthermore, it has been shown in [24] that customers may be able to follow the whole food production process via the use of blockchain technology in the food supply chain. The authors also provided a use case for using blockchain technology in Colombia's organic coffee sector. Additionally, [25] provides a blockchain-based food safety monitoring system that uses electronic product code (EPC) IoT tags. Specifically, this technology can use smart contracts to stop data tampering and privacy exposure. To demonstrate the effectiveness, a prototype of the recommended architecture has been put into use.
- **The Smart Grid:** Energy users' roles are changing from being sole consumers to prosumers who may produce energy (for example, from renewable energy resources) in addition to consuming it [26]. This is due to the growth of distributed renewable energy resources. When energy prosumers have extra energy, they could sell it to other consumers. P2P energy trading is what we refer to as energy trading between a prosumer and a consumer, or peers. In a dispersed setting, it might be challenging to provide two trading partners safe and reliable energy trading. With the advent of blockchain technology, P2P energy transaction may now be guaranteed to be safe. Recent studies have suggested using blockchain technology to get around these issues. For instance, a secure energy trading system based on consortium blockchains was created in [27]. This method may significantly reduce trading costs without using a central broker by utilising blockchains' distributed consensus. Additionally, a blockchain-based decentralised energy trading system was created by Aitzhan and Svetinovic [28]. In decentralised smart grid systems, this technology demonstrated its effectiveness in protecting confidential energy trade transactions. Additionally, a blockchain-based solution for safe and transparent energy demandside control on smart grids was presented in the work of [29].
- **Medical Care:** The ageing population makes health care one of the main social economic challenges; limited hospital resources create new complications for regular healthcare treatments. The potential for expanding remote health care services at home or in a clinic is presented by the most recent advancements in wearable medical technology and BDA in medical data. This might potentially alleviate the burden on hospital resources [30]. For instance, elderly people who remain in their homes wear medical devices on their bodies. These wearable devices continuously collect and monitor medical data, such as blood pressure, blood sugar, and heart rate. Through health care networks, physicians and medical teams may access health data from anywhere at any time. However, there are security and privacy hazards associated with looking at health care data. Health care networks' unpredictability and the vulnerability of medical equipment provide challenges for maintaining privacy and guaranteeing protection of medical records. Blockchain integration with health

care networks may be able to solve problems with data security and privacy. The study of [31], for instance, shows how using blockchain technology might safeguard medical records stored on cloud servers. In the meanwhile, [32] developed a blockchain-based system to guarantee the management of confidential health care data. For instance, smart contracts may be used to automatically collect and provide the system with health data generated by medical sensors, enabling real-time patient monitoring. Underlying blockchains may be used to maintain anonymity throughout the whole process. Additionally, [88] provided a blockchain-based system for storing personal health information and enabling data exchange across various medical facilities, hospitals, insurance providers, and individuals. Health care data security and privacy may be guaranteed throughout the process. Additionally, [33] suggested an attribute-based signature method for decentralised blockchain systems in the healthcare industry. This system may, on the one hand, confirm the authenticity of medical records and the identity of the data owner. Conversely, this tactic may also protect the owner of the health data's privacy. In order to ensure confidentiality and anonymity, the recent research [34] suggests an in-home therapeutic management system that combines blockchain-based MEC with IoT.

VI. Conclusion

The existing IoT systems are suffering a variety of difficulties including heterogeneity, poor interoperability, resource constraints, and privacy and security susceptibility. The recent appearance of blockchain technology effectively enables a solution to the concerns with the better interoperability, privacy, security, and traceability and dependability. In this study, we examine merging blockchain with IoT. We designate such combination of blockchain and IoT as BCoT. We provide a detailed survey on BCoT. In specifically, we first briefly explain IoT and blockchain technologies. We then discuss the prospects of BCoT and describe the architecture of BCoT. We next detail the research concerns in blockchain for next-generation networks. We further address the potential applications of BCoT and define the open research directions in BCoT.

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