Integration of Blockchain and Cloud of Things: Architecture, Applications and Challenges

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***Abstract*—The blockchain technology is taking the world by storm. Blockchain with its decentralized, transparent and secure nature has emerged as a disruptive technology for the next generation of numerous industrial applications. One of them is Cloud of Things enabled by the corporation of Cloud computing and Internet of Things (IoT). In this context, blockchain provides innovative solutions to address challenges in Cloud of Things in terms of decentralization, data privacy and network security, while Cloud of Things offer elasticity and scalability functionalities to improve efficiency of blockchain operations. Therefore, a novel paradigm of blockchain and Cloud of Things combination, called as the BCoT model, is regarded as a promising enabler for a wide range of applied scenarios. In this paper, we present a state-of-the-art review on the BCoT integration to provide general readers with the overview of the BCoT in various aspects, including background knowledge, motivation, and integrated architecture. Particularly, we also provide an in-depth survey of BCoT applications with extensive discussion on use-case domains as well as their opportunities in 5G networks and beyond. Compared to other relevant survey papers, we present a thorough review on the emerging BCoT platforms and services which are useful to researchers and application developers in identifying and catching up with the latest technologies in this fast-growing field. Moreover, research challenges and future directions are also highlighted.**

***Index Terms*—Blockchain, cloud computing, Internet of Things, Cloud of Things, security, industrial applications.**

I. Introduction

Recent years have witnessed the explosion of interest in blockchain, across a wide span of applications from cryptocurrencies to industries [1], [2], [3]. The rapid development in the adoption of blockchain as a disruptive technology is paving the way for the next generation of financial and industrial service sectors. Indeed, new research activities on blockchain and its applications take place every day, impacting many aspects of our lives, such as real estate [4], finance [5], energy [6], and government services [7].

From the technical perspective, blockchain is a distributed ledger technology that was firstly used to serve as the public digital ledger of cryptocurrency Bitcoin [8] for economic transactions. The blockchain is basically a decentralized, immutable and public database. The concept of blockchain is based on a peer-to-peer network architecture in which transaction information is not controlled by any single centralized entity. Transactions stored in a chain of blocks are publicly accessible to all blockchain network members in a trustworthy manner. Blockchain uses consensus mechanisms and cryptography to validate the legitimacy of data transactions, which guarantees resistance of linked blocks against modifications and alterations [9]. In particular, the blockchain technology also boasts the desirable characteristics of decentralization, accountability, and security which improve service efficiency and save significantly operational costs. Such exceptional properties promote the usage of applications built on blockchain architecture in recent years. Thus, it makes now the right time to pay attention to this hot research topic.

On the other side, the revolution in the field of information and communication has created a wealth of opportunities for advanced technologies, especially Internet of Things (IoT) and Cloud computing. IoT has reshaped and transformed our lives with various new industrial, consumer, and commercial services and applications [10], [11]. Typically, IoT is a system of physical objects that can be monitored, controlled or interacted with by ubiquitous electronic devices to enable ubiquitous computing services. IoT has been applied widely in numerous industrial systems such as smart cities, smart industries, healthcare, and agriculture. Unfortunately, due to the scarcity of memory, power and computational resources of IoT devices, they always delegate IoT application tasks to Cloud computing, which gives birth to the Cloud of Things (CoT) paradigm [12], [13]. The Cloud of Things model offers unlimited storage capabilities and processing power enabled by cloud services to IoT applications. Moreover, it provides a flexible, robust cloud computing environment which allows dynamic data integration from a massive network of IoT devices, showing great potentials to improve quality of user experience, system performance and efficiency of service delivery [14].

However, the conventional CoT infrastructures tend to be ineffective due to the following challenges. First, conventional CoT solutions have mainly relied on centralized communication models where IoT devices are connected, identified and managed by central cloud servers. This model is unlikely to scale when IoT networks become more widespread. Importantly, this completely centralized architecture also incurs bottleneck issues and singular points of failures which can lead to disruptions of the entire CoT network [15]. Second, most

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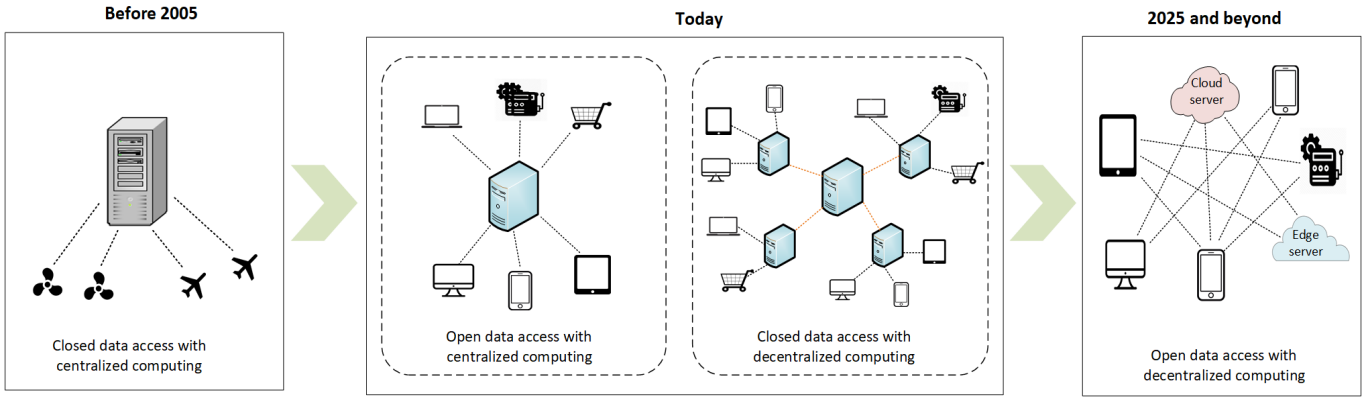

Fig. 1: Past, present and future Cloud of Things infrastructure.

of centralized CoT infrastructures mandate trusting a third party, i.e. a cloud service provider, for IoT data processing, which raises data privacy concerns. Indeed, the cloud sever will honestly perform the IoT computation, but meanwhile may obtain personal information without consent of users, which leads to serious information leakage and system security issues, accordingly. Third, IoT users have a lack of data ownership with traditional CoT ecosystems. With current CoT schemes, IoT owners have minimal control over their personal data and find it difficult to keep track of the exchange of their data over the cloud IoT environments. Final, the centralized network infrastructure results in higher communication latency and power consumption for IoT devices due to long data transmission, which hinders the large-scale deployments of CoT in practical scenarios [16].

With such critical challenges, a centralized architecture is not a viable solution for a decentralized and distributed CoT ecosystem with a large number of distributed IoT sensors and devices. In order to achieve a sustainable development and long-term adoption of CoT in various applications, building a more decentralized ecosystem is regarded as a future direction. Therefore, as illustrated in Fig. 1, the centralized computing schemes with closed data access paradigms have been upgraded to the open and semi-centralized cloud architectures which have been used widely in current applications. However, it is predicted that the future generation of the IT technology will be open and decentralized cloud IoT paradigms with the help of innovative blockchain solutions. Nowadays, blockchain, a decentralized, secure and transparent system, has emerged as a promising technology to address critical issues of conventional centralized networks and drive the next generation of CoT technologies. Particularly, the integration of blockchain and CoT leads to a novel paradigm which we call the *BCoT* paradigm. The combination of these emerging technologies brings great benefits to both worlds and thus gains sustainable interest of academics and industries. Specifically, the adoption of blockchain can provide potential benefits to CoT networks as follows.

- Decentralization: Blockchain with its decentralized nature is a promising methodology to effectively solve bottleneck and single-point failure issues by eliminating the requirement for a trusted third party in the CoT network [17]. The disruption of a blockchain node does not impact the operation of the BCoT network. Further, the peer-to-peer architecture of blockchain allows all network participants to verify IoT data correctness and ensure immutability with equal validation rights.
- Network security: The BCoT system can achieve a trustworthy access control by using blockchain-enabled smart contracts [18] which enable to authorize automatically all operations of cloud providers and IoT devices on cloud IoT environments. This mechanism can prevent potential threats to network resources and enhance fine-grained control on IoT data [19], which guarantees high network security.
- Data privacy: Thanks to immutable and trustworthy features of blockchain, building storage systems on blockchain is a highly efficient approach to protect IoT data against modifications. Blockchain is adopted to record evidence and events of data transactions in an integrity-preserved, authenticity-guaranteed manner via immutable hash chains and digital signatures. Importantly, the blockchain enables users to track their transactions over the network so as to maintain device and data ownership.
- Corporation: Blockchain enables a new cooperation ecosystem among multiple entities with unlimited data sharing capabilities without trusting each other. The removal of third party helps establish open environments where any IoT users and cloud providers interested in the system can participate and collaborate to achieve the common goals within the BCoT ecosystem [20]. This also enables fast expansion and high scalability of the BCoT networks.

On the other hand, CoT can support blockchain platforms with the following key benefits:

- Scalable support for blockchain transactions: In large-scale blockchain applications, the number of transactions in blockchain networks can be enormous. Therefore, it is highly necessary to provide powerful data processing services to accelerate transaction execution in order to enable scalable blockchain services. In this context, the cloud can offer on-demand computing resources for blockchain operations thanks to its elasticity and scalability capability [21]. For example, public clouds can offer a large-scale network of resources for blockchain

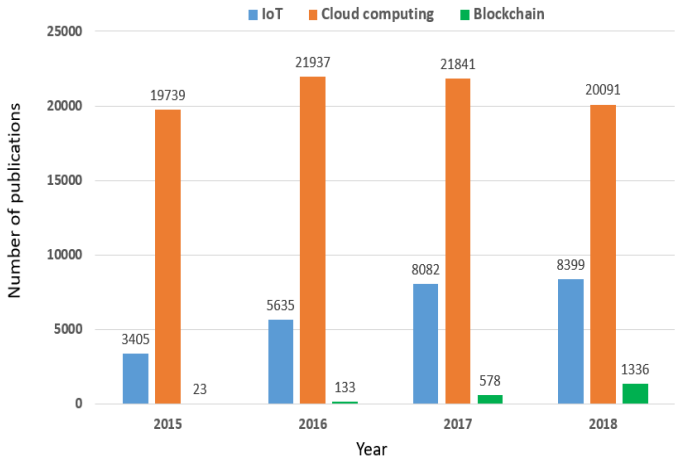

Fig. 2: Research trends about IoT, Cloud and blockchain (Source: Web of Science).

service operators in a federated cloud environment. Cloud services can help in such cases through the replication of blockchain data over the cooperative network and the use of instant computing resources available in each individual cloud. Therefore, the combination of cloud computing and blockchain can achieve a high scalability of the integrated system.

- Blockchain security: The implementation of blockchain algorithms on cloud computing may improve the security of the blockchain system itself. Cloud can use its security tools available to preserve blockchain transactions, and transaction data can be maintained in cloud database in a secure way.
- Fault tolerance: Cloud can help replicate blockchain data across a network of computing servers which are interconnected robustly by collaborative clouds [22]. This will minimize the single-failure risks due to the disruption of any cloud node and thus ensure uninterrupted services. Further, the inter-cloud ecosystem can enable the blockchain system to operate continuously in the event of a certain cloud server being under attack.

In short, the decentralization of CoT lays the ground for blockchain as data security and privacy solutions, and blockchain can leverage the cloud resources in CoT for intensive mining computations and reliable data storage. Hence, the integration of blockchain and Cloud of Things is expected to disrupt both current and future Information and Communication Technologies (ICT). The BCoT model can empower new scenarios for future smart objects, applications and services. Reviewing the state of the art in the field, we find that BCoT attracts enormous interests of research communities as shown in Fig. 2. Cloud computing and IoT have gained popularity in the last five years with considerable research publications. Interestingly, blockchain is increasingly becoming a hot research area in recent years with a fast-growing research trend, showing a really promising topic for both academics and industries in the future. The sustainable development of Cloud of Things and blockchain will drive breakthrough innovations to empower intelligent services and applications.

A. *Related works and contributions of this survey*

Many studies in Cloud of Things, blockchain and related issues have been investigated over the recent years in a wide range of technical aspects. Many efforts have been made to provide review articles on this research area in different scopes. The survey papers [23], [24], [25] presented the review of recent efforts in the adoption of blockchain technology in various IoT scenarios and applications. They also analysed technical aspects of blockchain-IoT combinations, from definition, integrated architectures, enabling technologies to application scenarios and open issues. Meanwhile, the authors in [26] discussed research issues, challenges and opportunities of combination between blockchain and cloud computing. They focused on the advantages of blockchain adoption in cloud networks, including security, data management and application domains with potential service platforms. The work [27] presented a survey on the use of the blockchain technology to provide security services and its technical properties to solve associated challenges in various application domains, including IoT and Cloud computing. More recently, the overview on the integrated model of blockchain and edge computing, an extended cloud computing concept, was discussed in the survey [28]. Table I summarizes the main topics and contributions of the previous related surveys on the integration of blockchain, cloud computing and IoT technologies as well as major contributions of our review paper.

TABLE I: Surveys on blockchain and Cloud, IoT technologies.

Paper	Topic	Main contributions
[23]	Blockchain and IoT	A survey of blockchain protocols for IoT, research issues and challenges of IoT-blockchain integration.
[24]	Blockchain and IoT	A comprehensive survey of underlying blockchain concepts, architectures, applications for IoT.
[25]	Blockchain and IoT	A brief review on the usage of blockchain for IoT.
[26]	Blockchain and Cloud	A brief survey of blockchain in cloud computing and its security solutions for cloud-based applications.
[27]	Blockchain and Cloud	An introduction of blockchain for cloud platforms with associated challenges opportunities.
[28]	Blockchain and edge computing	A systematic survey of the combination of blockchain and edge computing
This paper	Blockchain and Cloud of Things	A comprehensive review on the integration of blockchain and Cloud of Things (BCoT) with a detailed discussion on concepts, motivations, and architectures. Specially, the state-of-the-art survey on the BCoT applications, BCoT platforms is provided with challenges and future research directions.

Although blockchain and Cloud of Things have been studied extensively in the literature works, there is no existing work to provide a comprehensive survey on the combination of these important research areas, to our best knowledge. In comparison to the above review works, in this paper, we provide a state of the art survey on the integration of blockchain and Cloud of Things with extensive discussions on many aspects, ranging from concept background, integrated architectures to application domains, and research challenges. We also discuss the latest advances in BCoT and present the newest platforms

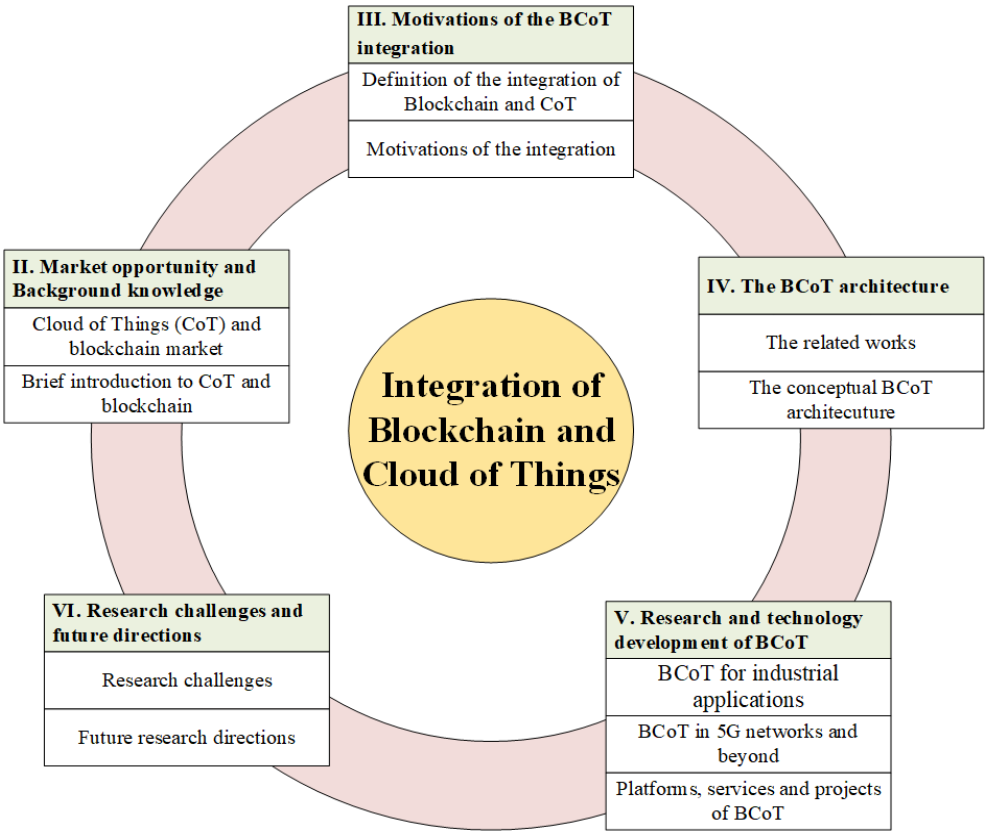

Fig. 3: Organization of the paper.

and services of the emerging BCoT models. The main goal of this survey is to provide readers with thorough knowledge of the blockchain and Cloud of things integration which is collected from respective websites, technical reports, academic articles and newspapers. Specially, our review paper can help academics, researchers, and industrialists to be informed of the most recent BCoT solutions in the industry's marketplace. Accordingly, they can keep up-to-date with advanced technology trends, industry requirements, technical challenges and innovation opportunities, all of which can be very useful to their BCoT project development.

The main contributions of this survey can be highlighted as follows.

1) We provide a state of the art survey on the corporation of blockchain and Cloud of Things with a comprehensive discussion on different technical aspects, from market opportunities, BCoT background, integration motivations to the conceptual BCoT integrated architecture.
2) We present the updated review on the use of BCoT models in various application domains. We also analyse the benefits of BCoT adoption and important lessons learnt from BCoT adoption in each use case.
3) We explore opportunities of BCoT in the next generation 5G networks.
4) From the extensive review on BCoT integrations, we identify possible research challenges and open issues in the field. Potential research solutions for each challenge are also provided to encourage scientists and application developers to put more research efforts in this promising area.
5) Finally, some future research directions are also explored to extend the scope of BCoT in future services and applications.

B. *Structure of the survey*

The structure of this survey is organized as Fig. 3. Section II provides a summary of market opportunities enabled by the development of blockchain and Cloud of Things. Then, the background knowledge of both blockchain and Cloud of Things is also described. The motivations of the BCoT integration are explained in Section III. Meanwhile, the conceptual BCoT architecture is presented in Section IV. We review the recent developments of BCoT in Section V with extensive discussion of benefits of BCoT models in a wide range of industrial applications. Moreover, the advantages of the BCoT paradigm in 5G networks are investigated. Specially, we also highlight the development of BCoT with the latest advances in platforms, services and research projects. Final, research challenges and future directions are outlined in Section VI.

II. Market Opportunity and Background Knowledge

In this section, we first highlight the development of BCoT market and its impacts on global economy. Then, background knowledge of blockchain and Cloud of Things is also provided.

A. Market opportunity

The rapid development of CoT and blockchain brings enormous market opportunities for manufacturers and service providers. In this section, we present the opportunities brought by these disruptive technologies and their impacts on global economy.

- *Cloud of Things market:* According to research group Gartner, by 2020 there will be more than 26 billion connected devices in use by businesses and individuals [29]. As a long-term prediction, Cisco forecasts that 500 billion IoT devices are expected to be connected to the Internet by 2030 [30]. More recently, GlobeNewswire predicts that the global 5G IoT market is forecasted to grow from USD 694.0 million in 2020 to USD 6,285.5 million by 2025 [31]. Meanwhile, the worldwide public cloud service market is projected to grow 17.5 percent in 2019 to total $214.3 billion, up from $182.4 billion in 2018, and is expected to achieve $331.2 billion in 2022, according to Gartner [32]. Moreover, the cloud vendor revenue is projected to reach $493 billion by 2026, showing an increase of over $200 billion from 2018 [33].

Regarding the development of Cloud of Things, in a new report from MarketsandMarkets [34], the CoT platform market is estimated to grow from USD 1.88 billion in 2016 to USD 7.15 billion by 2021. Beyond this prediction, Absolute Markets Insights [35] reported that the global CoT market accounted for US$ 2.42 billion in 2017 for three main services (device management, connectivity management and application enablement) and all CoT application domains. They also expect that CoT will reach US$ 8.14 billion by 2022.

- *Blockchain market:* According to the CSIRO research group [36], global funding for blockchain was growing at an accelerated pace, up from AUD$1.9 million in 2012 to AUD$7.6 billion in November 2018. Global Market Insights [37] estimates a 50% increase in the number of investments in blockchain-related start-ups from 2016-2017, and the blockchain industry will surpass $16 billion by 2024. Besides, WinterGreen Research predicts that blockchain markets will head to $60 Billion Worldwide by 2024 [38].

These above statistics point out the significance of Cloud of Things and blockchain in global business transformation with growing economic roles. Importantly, the predictions show the rapid progression of these innovative technologies which are expected to make great contributions to the world industry revolution in the future Internet.

B. Background knowledge

1) Brief introduction to Blockchain: Blockchain is mostly known as the technology underlying the virtual cryptocurrency Bitcoin which was invented in 2008 by a person known as Satoshi Nakamoto [8]. In a nutshell, the blockchain is briefly explained as public, trusted and shared ledger based on a peer-to-peer network. This emerging technology has also recently become a hot topic for researchers and been argued to innovate blockchain-based applications beyond Bitcoin. The core idea of the blockchain network is decentralization which means blockchain is distributed over a network of nodes. Each node has the possibility of verifying the actions of other

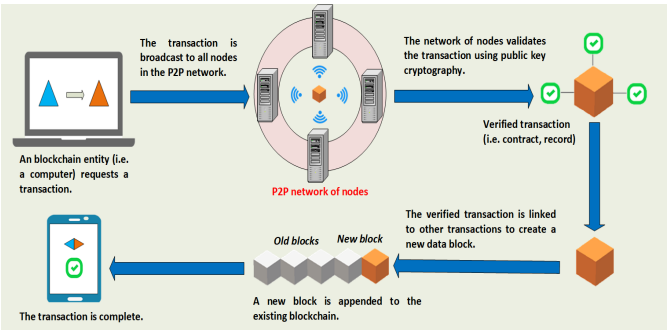

Fig. 4: The concept of blockchain operation.

entities in the network, as well as the capability to create, authenticate and validate the new transaction to be recorded in the blockchain. This decentralized architecture ensures robust and secure operations on blockchain with the advantages of tamper resistance and no single-point failure vulnerabilities. In particular, blockchain can be accessible for everyone, but not still controlled by any network entity. This concept is enabled through the interoperability of all network nodes by complying strict rules and common agreement, which is called as consensus to achieve distributed database synchronization over the blockchain network. The general concept on how blockchain operates is presented in Fig. 4.

In order to realize the potentials of blockchain in Cloud of Things, it is vitally important to understand the operation concept, main properties of blockchain, and understand how blockchain can bring opportunities to CoT applications. In this section, we first present the main components of a blockchain network. Next, we discuss the key characteristics of blockchain in terms of immutability, security, and integrity.

1.1) Main components of blockchain

Blochain has several key components which are summarized as the following.

- *Data block:* Blockchain is essentially a chain of blocks, a linear structure beginning with a so-called genesis block and continuing with every new block linked to the chain. Each block contains a number of transactions and is linked to its immediately-previous block through a hash label. In this way, all blocks in the chain can be traced back to the previous one, and no modification or alternation to block data is possible. Specially, a typical structure of data block includes two main components, including transaction records and a blockchain header [39]. Here, transaction records is organized in a Merkle tree based structure where a leaf node represents a transaction of a blockchain user. For example, a user can make a request with associated metadata (i.e. transferred money or contract) to establish a transaction that is also signed with users private key for trust guarantees. Meanwhile, the block header contains the following information: 1) hash of the block for validation, 2) Merkle root to store a group of transactions in each block, 3) nonce value which is a number that is generated by consensus process to produce a hash value below a target difficulty level, and 4) timestamp which refers to the time of when the block is created. A typical blockchain structure can be seen as Fig. 5.

- *Distributed ledger (database):* Distributed ledger is a type

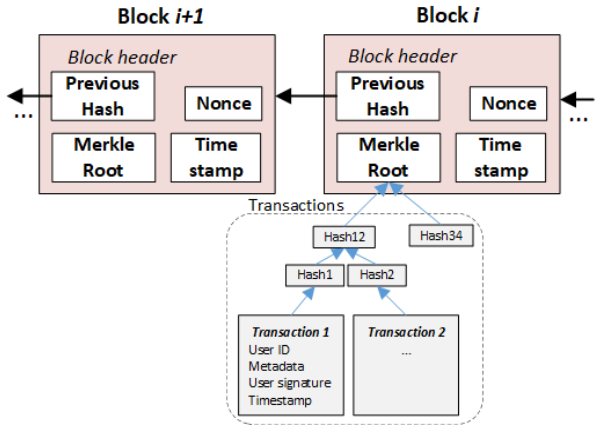

Fig. 5: The data block structure.

of database which is shared and replicated among the entities of a peer-to-peer network. The shared database is available for all network participants within the blockchain ecosystem. Distributed ledger records transactions similar to the process of data exchange among the members of the network. Participants of the network can achieve on the agreement by a consensus mechanism in a distributed environment where no third party is required to perform the transaction. For example, if a person joins the Bitcoin application, then he has to abide by all rules and guidelines which are established in the programming code of the Bitcoin application. He can make transactions to exchange currency or information with other members automatically without a third party such as a financial institution. In the distributed ledger, every record always has a unique cryptographic signature associated with timestamp which makes the ledger auditable and immutable. Further, the removal of the central point of control also ensures high fairness among blockchain participants and enhances security of the system.

- *Consensus algorithms:* When nodes start to share or exchange data on a blockchain platform, there is no centralized parties to regulate transaction rules and preserve data against security threats. In this regard, it is vitally necessary to validate the block trustfulness, keep track the data flow and guarantee safe information exchange to avoid fraud issues, such as double-spending attacks [40]. These requirements can be met by using validation protocols called as consensus algorithms. In the blockchain context, a consensus algorithm is a process used to reach agreement on a single data block among multiple unreliable nodes. An example of consensus applications is in Bitcoin blockchain. Bitcoin adopts a Proof of Work algorithm (PoW) [8] as an enabling consensus mechanism run by miners to ensure security in a untrusted network. Software on the network of miners uses their computation resources to solve complex mathematical puzzles. The first miner solving the puzzle to create a new block will receive a reward as an encouragement for future mining contributions. However, a critical drawback of PoW is its high resource consumption which would be unsustainable in the future. As a result, other efficient consensus algorithms appears as strong alternatives, such as Proof-of-stake (PoS), Byzantine Faulty Tolerant (BFT). Details of conceptual features and related technical issues of such consensus algorithms can be referenced to previous excellent surveys [41], [42].

- *Smart contracts:* A smart contract is a programmable application that runs on a blockchain network. Since the first smart contract platform known as Ethereum [43] was released in 2015, smart contracts have increasingly become one of the most innovative topics in the blockchain area. When we talk about smart contracts, the natural question is: What makes smart contracts so smart? This is due to their self-executing nature which means the codes will execute automatically the contractual clauses defined in the contract once the conditions have been met. For example, when a person signs a smart contract to transfer his funds, the funds will transfer automatically themselves over the blockchain network. Then the transfer information will be recorded as a transaction which is kept on the blockchain as an immutable ledger. Such a type of self-executing agreement relying on the code makes smart contracts unalterable and resistant to external attacks [44].

In addition to the capability of defining the operational rules and penalties around an agreement similar to the way a traditional contract does, smart contracts is capable of automatically enforcing their obligations to manage transactions. Particularly, smart contracts allow the performance of credible transactions without requiring the involvement of middlemen or third-party intermediaries [45]. This property is particularly useful because it significantly reduces the issues of confliction and saves operation time as well as system costs. Therefore, smart contracts can provide cheaper, faster and more efficient options compared to the traditional systems in which contract conditions are always enforced physically by a central authority, enforcement mechanism or guidance system.

With its programmable and automatic features, smart contracts offer a wide range of new applications to solve real-world problems, such as financial services and insurance, mortgage transactions, supply chain transparency, digital identity and records management. To have a better understanding of smart contract applications, an example of car purchase contract is given in Fig. 6. In this use case, Bob wants to sell a car and Alice is a person looking for a car. Bob defines the selling conditions using the car contract available on blockchain, while Alice needs to sign the contract using his private key so that he can transfer the money to buy the car. The contract is broadcast on the blockchain network where all participants can validate the contract terms. If all members achieve an agreement on the contractual clauses, Alice automatically obtains the access code to the smart lock for the garage. The blockchain system then registers Alice as the new owner of the car. Obviously, by adopting blockchain, transactions can be executed without the need of third party authorities such as lawyers or financial institutions, which ensures transparency, time-efficiency and trustfulness.

1.2) Blockchain categories

Blockchain can be classified into two main categories, including public (or permission-less) and private (or permissioned) blockchain. A public blockchain is an open network which means it is accessible for everyone to join and make transactions as well as participate in the consensus process.

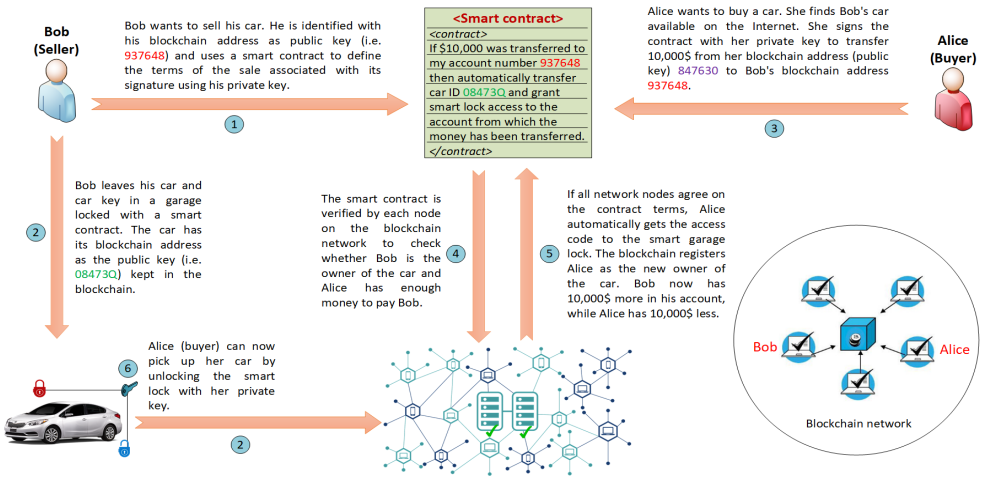

Fig. 6: An example of smart contract implementation on car purchase.

TABLE II: Popular blockchain platforms.

Platforms	Consensus	Operation Modes	Smart contract support?	Programming language	Latest version	Open source?
Bitcoin	PoW	Public	Yes	Ivy, RSK, BitML	v0.18.0, May. 2019	Yes [46]
Ethereum	PoW, PoS	Public and permissioned	Yes	Solidity, Flint, SCILLA	v1.8.27, Apr. 2019	Yes [47]
Hyperledger	PBFT	Permissioned	Yes	Go, Node.js, Java	v2.0 Alpha, Apr. 2019	Yes [48]
IBM Blockchain	PoW, PoS	Permissioned	Yes	Go, Java	v2.0, Jun. 2019	Yes [49]
Multichain	PBFT	Permissioned	No	C++, Go, Java, Python, PHP	beta 2.0, Mar. 2016	Yes [50]
Hydrachain	PoW, PoS	Permissioned	Yes	Python	hydrachain 0.3.2, 2018	Yes [51]
Ripple	PoW	Permissioned	Yes	C++	v1.2.4, Apr. 2018	Yes [52]
R3 Corda	PoW, PoS	Permissioned	Yes	Kotlin, Java	V4.0, Feb. 2019	Yes [53]
BigChainDB	BFT	Public and permissioned	Yes	Java	v2.0.0b9, Nov. 2018	Yes [54]
Openchain	Partionned	Consensus	Yes	C++, Java	v0.7.0, Nov. 2017	Yes [55]
Chain core	Federated consensus	Permissioned	Yes	Go	v.1.2, Jun. 2018	Yes [56]

The best-known public blockchain consists of Bitcoin and Ethereum with open source and smart contract blockchain platforms. Meanwhile, private blockchain is an invitation-only network managed by a central entity and all participations in blockchain for submitting or writing transactions have to be permissioned by a validation mechanism.

The invention of Bitcoin and especially the appearance of the next blockchain generation Ethereum have strived continuously toward improvement of the blockchain technology. In the past few years, numerous blockchain platforms have emerged and applied to industrial and financial applications. In this article, we select and survey the most popular and promising platforms as summarized in Table II. We compare different blockchain platforms in many aspects, namely consensus process, operation modes, smart contract support, programming language and the latest version of each platform. In particular, the open source link of each blockchain platform is also provided with available codes for ready usage. Information of other blockchain platforms can be found in recent articles [45], [57].

1.3) Key characteristics of blockchain

In summary, blockchain has several main characteristics, including immutability, decentralization, transparency, security and privacy, all of which can be highly beneficial to Cloud of things applications. We will briefly review such key properties as the following.

Immutability: It is the ability for a blockchain ledger to keep transaction data unchangeable over time. Technically, transactions are timestamped after being verified by the blockchain network and then included into a block which is secured cryptographically by a hashing process. It links to and incorporates the hash of the previous block. This mechanism connects multiple blocks together and builds a chronological chain. Particularly, the hashing process of a new block always contains metadata of the hash value of previous block, which makes the chain strongly unalterable. In this way, it is impossible to modify, change or delete data of the block after it is validated and placed in the blockchain. Any attempts on transactions in the chain will be rejected by the subsequent blocks, and such modifications will be easily detected.

Decentralization: The decentralized nature of blockchain means that it does not rely on a central point of control to manage transactions. Instead of depending on a central authority or third party to perform transactions between network users, blockchain adopts consensus protocols to validate transactions in a reliable and incorruptible manner. This exceptional property brings promising benefits, including eliminating single point failure risks due to the disruption of central authority, saving operational costs and enhancing trustworthiness.

Transparency: The transparency of a blockchain stems from

the fact that all information of transactions on blockchain is viewable to all network participants. In other words, the same copy of records of blockchain spreads across a large network for public verifiability. As a result, all blockchain users can fully access, verify and track transaction activities over the network with equal rights. Such transparency also helps to maintain the integrity of the blockchain-based systems by reducing risks of unauthorized data alternations.

Security and privacy: One of the most appealing aspects of blockchain technology is the degree of security and privacy that it can provide. The key aspect of security in blockchains is the use of private and public keys. Blockchain systems use asymmetric cryptography to secure transactions between members. These keys are generated randomly with strings of numbers so that it is mathematically impossible for an entity to guess the private key of other users from their public key. This preserves blockchain records against potential attacks, reduces data leakage concerns and improves security of blockchain network [58]. Additionally, the privacy service provided by blockchain and smart contract gives the data provenance rights to users. In other words, this ability enables data owners to manage the disclosure of their information on blockchain. Specially, by setting access rules on self-executing smart contracts, blockchain guarantees data privacy and data ownership of individuals. Malicious access is validated and removed by user identity capability and authorization of smart contract.

2) Brief introduction to Cloud of Things: In this section, we will introduce the key concept of Cloud of Things and then present their main features.

2.1) Cloud of Things concept

Nowadays, Internet of Things (IoT) have constituted a fundamental part of the future Internet and drawn increasing attention from academics and industries thanks to their great potentials to deliver exciting services across various applications. IoT seamlessly interconnects heterogeneous devices and objects to create a physical environment where sensing, processing and communication processes are implemented automatically without human involvement. However, massive volumes of data generated from a large number of devices in current IoT systems become a bottleneck in guaranteeing the desired Quality of Service (QoS) because of constrained power and storage resources of IoT devices.

Meanwhile, cloud computing has unlimited resources in terms of storage and computation power, which can provide on-demand, powerful and efficient services for IoT use domains. Especially, the convergence of cloud computing with IoT paves the way for a new paradigm as Cloud of Things, which can empower both worlds. Indeed, the wealth of resources available on the cloud is highly beneficial to IoT systems, while cloud can gain more popularity in real-life applications from integrating with IoT platforms [59]. Moreover, Cloud of Things can transform current IoT service provision models with minimal management effort, high system performance and service availability.

The general concept of Cloud of things is shown in Fig. 7 with a network architecture of IoT devices, cloud computing, analytic services and application layer. In this hierarchy,

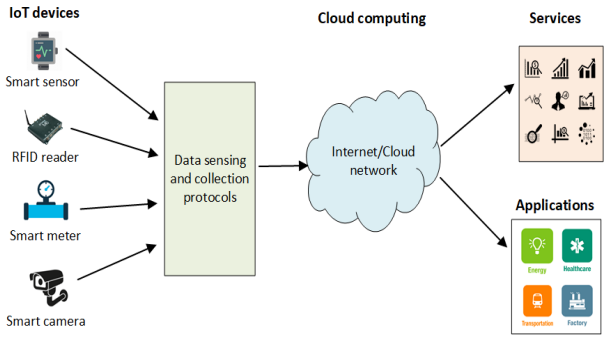

Fig. 7: The general concept of Cloud of Things.

IoT devices are responsible to sense and collect data from local environments. However, due to their limited computing resources, IoT devices will transmit recorded data to the cloud for data acquisition. Cloud computing can provide a powerful capability of data processing and storage. Analytic services can be provided to support IoT systems, such as historic data monitoring, information storage or statistical analysis. The results of cloud data processing are used to serve end applications, aiming to facilitate IoT service provisions and meet requirements of end users.

2.2) Key characteristics of Cloud of Things

The Cloud of Things platforms can enable ubiquitous applications and smart services by the following main characteristics.

On-demand service: The Cloud of Things platform can offer instant services to users anywhere and anytime thanks to automatic resource provision capabilities of cloud computing. It enables autonomous service delivery without the need of human engagement, which ensures that physical and virtual resources such as storage, processing, memory, and virtual machines can be provisioned to end users rapidly and seamlessly.

High processing capacity: With unlimited virtual processing capabilities of cloud computing, Cloud of Things open up new opportunities to enhance IoT computation by enabling data offloading and executing data remotely. This not only improves computation abilities of local devices, but also addresses effectively issues of IoT systems in terms of energy saving and bandwidth preservation. Specially, when the big data era comes which is featured by its enormous amount of data generated by billions of devices, resourceful Cloud of Things can offer highly effective computing services to deal with data integration, aggregation and computation for complex IoT applications [60].

Automatic management: Cloud of Things can offer simplified and automatic IT maintenance and management solutions by exploiting cloud servers, virtual machines and resource infrastructure. IoT users can interact easily with cloud computing to implement functionalities without any requirement for software installation as well as human involvement. Access control and data usage over the IoT networks can be controlled effectively by cloud administrators with high performance and low operational costs.

Ubiquitous communication: Application and data sharing are two important features of the Cloud of Things paradigm. The provision of system management models available on

clouds supports well boundless communications and interconnections between IoT devices together, between things and users to empower ubiquitous applications. Particularly, the integrated paradigm of cloud and IoT drives advanced network management and ubiquitous communication technologies for system design, operation control, and QoS management. Such ubiquitous applications will promote the comprehensive collaborations of multiple IoT ecosystems in the future Internet.

Scalability: The exponential growth of IoT devices and scalability of cloud platforms, i.e. multi-clouds, is sufficient for the building of large-scale IoT applications, allowing service providers to deliver and extend continuously their markets. This paves the way to the emerging scalable service models, such as smart industry or smart healthcare [61] where coordination of inter-cloud systems and interconnection of numerous IoT devices play an integral role in the large-scale service platforms. Beyond that, by enabling cloud IoT services, the scalable storage capabilities of clouds can be particularly useful to handle big data of IoT networks and guarantee robustness of the scalable application.

In summary, in this section, we provide a brief introduction of the key concepts and important features of both blockchain and Cloud of Things technologies. In the next section, we discuss the motivation of the integration of these innovative technologies.

III. Motivations of integration of blockchain and Cloud of Things

In this section, we present the motivations of the integration of blockchain and Cloud of Things. We first explain the definition of the integration, then describe the motivations for the integration stemming from challenges of each area and opportunities brought by corporations such two technologies.

A. Definition of the integration of Blockchain and Cloud of Things

To highlight the motivation, we recall the most important properties of both technologies for the integration. Blockchain brings the capability of storing and managing cloud IoT data through its secure distributed ledge. More importantly, blockchain can provide a series of security features such as integrity, transparency and privacy, all of which promise to tackle efficiently security issues of current Cloud of Things networks. Thus, the main points of blockchain here are its security benefits to Cloud of Things and the need for scalability improvement.

On the other side, Cloud of Things considered in this paper refer to the combination of cloud computing and IoT. Specifically, cloud computing with its large resources can offer powerful computation and massive storage services with efficent data management, while IoT provides the ability of sensing, interconnecting and communicating with physical devices across different applied scenarios. The Cloud of Things resulted from convergence of such technologies are expected to address comprehensively various real-world problems, including effective data storage, communication and service provisions. Therefore, the main points of Cloud of Things here are its advantages of providing scalable services and the need for security improvement.

Reviewing the rich and state of the art articles in the field, the motivation behind the integration of blockchain and Cloud of Things (BCoT) stems mainly from the complementary properties and limitations of these technologies. The combination of such innovative technologies promises to solve effectively existing challenges in both worlds and open up new opportunities to empower BCoT-based applications.

In the following, we discuss the motivation of the integration and then present opportunities brought from the BCoT integrations.

B. Motivation of integration of Blockchain and Cloud of Things

In this subsection, we highlight the motivation of the integration which comes from the security challenges of Cloud of Things, technical limitations of blockchain and the promising opportunities brought by the incorporation of such two technologies.

1) Security challenges in Cloud of Things: Cloud of Things support ubiquitous computing services with large data storage and high system performance. However, their security is still a critical challenge [62], [63]. In dynamic Cloud of Things environments, massive computation tasks are outsourced from IoT devices to the cloud, which has brought about a series of new challenging security issues, including data availability, unauthorized data sharing, data privacy management, confidentiality, identity management and access control.

Data availability: In current cloud network architectures, cloud services are provided and managed centrally by the centralized authority. However, this configuration is vulnerable to single-point failures, which bring threats to the availability of cloud services for on-demand IoT access. A centralized cloud IoT system does not guarantee seamless provisions of IoT services when multiple users request simultaneously data or cloud servers are disrupted due to software bugs or cyber-attacks.

Privacy management: Although the centralized cloud IoT can provide convenient services, this paradigm raises critical concerns related to user data privacy, considering a large amount of IoT data being collected, transferred, stored and used on the dynamic cloud networks. In fact, IoT users often place their trust in cloud providers managing the applications while know very little about how data is transmitted and who is currently using their information [64]. In other words, by outsourcing data protection to the cloud, IoT data owners lose control over their data, which has also adverse impacts on data ownership of individuals. Moreover, even in the distributed cloud IoT paradigms with multiple clouds, IoT data are not fully distributed but stored in some cloud data centres at high density [65]. In this context, a massive amount of IoT data may be leaked and user privacy is breached if one of the cloud servers is attacked.

Identity management: The secure and reliable management of identities is of significant importance for Cloud of Things systems. Traditional approaches have used Federated Identity

Management (FIM) structures where identity providers and service providers corporate to enable identity federation (i.e. in multi-cloud networks) [66]. However, this model has to be predefined manually with complex public key infrastructure. Obviously, such an identity management model is unsuitable for dynamic environments like cloud IoT. To provide a comprehensive and efficient user identity solution, an authentication mechanism should be created dynamically based on current user access rather than being manually managed by a central authority.

Data integrity: The storage and analysis of IoT data on clouds may give rise to integrity concerns. Indeed, due to having to place trust on the centralized cloud providers, outsourced data is put at risks of being modified or deleted by third parties without user consent. Moreover, adversaries can tamper with cloud data resources for financial or political purposes [67], all of which can breach data integrity. For these reasons, many solutions have been applied to overcome the problem, by using public verification schemes where a third party auditor is needed to perform the integrity verification periodically. This scheme potentially raises several critical issues, including irresponsible verification to generate bias data integrity results or invalidated verification due to malicious auditors. Importantly, most current public verification schemes mainly rely on the public key infrastructure (PKI) to control certificate of users for integrity verification, which suffers from management problems such as certificate storage, revocation and authentication. Therefore, developing new solutions to solve efficiently data integrity challenges is vitally necessary for Cloud of Things systems.

Access control: In cloud IoT systems, IoT users always have the demands to secretly share their data to service providers or third parties for service request (i.e. medical care request in health applications). In such contexts, an access control mechanism is of paramount importance for user identification and authentication. Traditional access control solutions have been built on attribute-based encryption technologies which require a trusted private key generator (PKG) for setting the access control policy system on clouds. However, a challenge here is that it is difficult to find a reliable PKG in practice. Further, it is proven that such a system can confront the problems of key abuse and loss of data ownership [68]. Even in the federated cloud networks with distributed cloud entities, access control enforcement is still vulnerable to adversaries that can compromise the access control system [69].

2) Technical limitations of blockchain: Although blockchain has its unique promise to disrupt services like Cloud of Things, it still remains several critical challenges in its development in terms of scalability, complexity, and security flaw.

Scalability: The current blockchain systems have serious scalability bottlenecks with constrained throughput, capacity and cost. Currently, many blockchains have long waiting time for transactions to be appended into the chain because of block size limitations. Therefore, the block generation time increases rapidly, which limits the overall system throughput. Further, if all transactions are stored in a chain, the blockchain capacity will become very large to maintain on the chain over time [70]. Considering complex IoT scenarios, i.e. smart cities, the IoT data is enormous and thus will result in the rapid growth in the IoT blockchain size, making it difficult to process high volumes of data. Because of such limitations, many application developers do not consider blockchain as a visible solution for large-scale systems [71].

Complexity: In IoT networks, in order to implement validation on transactions, IoT devices act as blockchain participants to run the consensus process to solve complex mathematical puzzles, which requires powerful computation hardware. Unfortunately, this is challenging to meet such requirements due to constraints of IoT resources. Even in the case of IoT devices with relatively high computing capacities, complexity of blockchain process can cost intensive resources involving electricity and human management. This would raise concerns of users about high operational costs which would hinder wide deployment of blockchain-based systems.

Security flaw: The final limitation of current blockchains may be unavoidable security flaw. If more than half of computers working as blockchain nodes to control computing power, attackers may modify consensus architectures and prevent new transactions from obtaining confirmations for malicious access. This is also called as 51% attack which is highlighted in the Bitcoin concept. Without having a comprehensive transaction management, blockchain can be put at risks of data breach and system damage.

In short, the decentralization of CoT lays the ground for blockchain as data security and privacy solutions, and blockchain can leverage the cloud resources in CoT for intensive mining computations and reliable data storage.

3) The opportunities of integration of blockchain and Cloud of Things: Based on complementary roles of blockchain and Cloud of Things as well as their potential advantages, the incorporation of such disruptive technologies opens up a wide range of BCoT opportunities, as summarized in the following.

Decentralization management: Motivated by the fully decentralized nature of blockchain, it is possible to build a decentralized BCoT management architecture under the distributed control of peer-to-peer network of cloud nodes and IoT devices. All blockchain peers maintain identical replicas of the ledger data records through decentralized consensus, and trustfulness is shared and distributed equally among the network entities. This decentralized structure eliminates totally single point failure bottlenecks, prevents efficiently disruption of BCoT services, and enhances significantly data availability.

Improved data privacy: The dynamic process of outsourcing IoT data to clouds and data exchange between cloud providers and IoT users are vulnerable to information disclosure and attacks caused by adversaries or third parties. Blockchain with its immutability, integrity and transparency properties is highly suitable for data protection in Cloud of Things networks. In fact, to launch a data modification attack in a BCoT system, an adversary would try to modify the records or alter data placed in blockchain. However, this is nearly impossible in practical scenarios where blockchain is preserved and controlled by secure and immutable consensus mechanisms. As a result, properties inherent to blockchain can significantly enhance data privacy for BCoT applications.

Improved system security: Blockchain can provide solutions to improve security for Cloud of Things, through the ability to offer important security properties such as confidentiality and availability inherent in blockchain. Indeed, in BCoT networks, all records on the blockchain are cryptographically hashed and transactions are signed by participants so that all user interactions with clouds remain confidential under blockchain-enabled signatures. Furthermore, with the decentralization feature inherent in blockhain, data is replicated across all network members with no single of failure bottlenecks, and thus BCoT promises to provide improved availability. Specially, the resourceful cloud computing can provide off-chain storage solutions to support data availability of the on-chain storage mechanisms once the main BCoT network is interrupted due to external attacks. On the other side, the implementation of blockchain algorithms on clouds may enhance security of the blockchain system itself. For example, clouds can use their available network security tools to maintain and preserve blockchain software, i.e. mining mechanism, against potential threats. The advantage of cloud computing for blockchain is proven through recent successful integration cloud-blockchain projects, such as Oracle blockchain (2017) and iExec blockchain (2018) projects [72].

Improved corporation: Incorporating the blockchain concept into BCoT systems with multi-clouds is regarded as a promising research topic. By adopting blockchain, BCoT enables to corporate boundlessly cloud service providers with IoT users without the requirement of central authority. In such architectures, IoT data is transferred securely in untrusted environments under the management of blockchain. User anonymity is also ensured due to blockchain to hidden sensitive information of users to avoid potential data leakage issues. Particularly, the use of smart contracts in blockchain allows secure data sharing in corporative BCoT networks, by offering automatic user authentication and data access capabilities without trusting any third parties. Therefore, it is possible to improve corporation in BCoT to pave a way for future large-scale IoT applications.

Reduced system complexity: By integrating blockchain with cloud computing, BCoT can reduce significantly complexity of system implementations. This integration is known as blockchain-as-a-service, where well defined platforms are available to set up and run blockchain for BCoT projects without worrying about underlying hardware technologies [73]. Moreover, blockchain algorithms now can be run online using cloud infrastructure, which is promising to reduce resource costs for running blockchain. Obviously, the convergence of blockchain and Cloud of Things opens up various opportunities to accelerate BCoT deployments on the large scale with simple and cheap implementations.

IV. The architecture of integration of blockchain and Cloud of Things

In this section, we review thoroughly the literature studies towards the integrated BCoT models of blockchain and Cloud of Things. We then propose a conceptual BCoT architecture with the fundamental concept and basic ideas of the integration which would be applicable to various scenarios.

A. Related works

With the current growing interest in the blockchain and Cloud of Things, many new integrated BCoT platforms and systems have been proposed in the literature studies to provide security solutions and applications [74], [75], [76], [77], [78]. The study [79] proposed a cloud-centric IoT framework enabled by smart contracts and blockchain for secure data provenance. Blockchain incorporates in cloud computing to build a comprehensive security network where IoT metadata (i.e. cryptographic hash) is stored in blockchain while actual data is kept in cloud storage, which makes it highly scalable for dense IoT deployments. In the solution, smart contracts with its autonomous, open and immutable properties are also adopted to ensure high cloud data validity. Meanwhile, a secure data sharing architecture was introduced in [80] with attributed based-access control cryptosystem. Its network model consists of four main components: IoT devices, a data owner, a blockchain network and a cloud computing platform. More specific, a permissioned blockchain model is adopted to manage IoT transactions and perform access control for device requests received by cloud, while cloud monitors closely the blockchain network. As a result, such a BCoT integration brings a comprehensive security framework with enhanced privacy preservation, data ownership and secure data sharing. Similarly, a hierarchical access control structure for BCoT was investigated in [81] with a blockchain-based distributed key management. Specially, the blockchain network topology involves distributed side blockchains deployed at fog nodes and a multi-blockchain operated in the cloud, which would speed up access verification offer flexible storage for scalable IoT networks. In addition, to protect BCoT in security-critical applications, a forensic investigation framework is proposed using decentralized blockchain [82]. Security issues from dynamic interactions between cloud service providers, clients, and IoT devices were considered and analysed with a tamper-evident scheme. Blockchain is performed to audit evidence during the investigation of a criminal incident among BCoT entities in a decentralized manner, and therefore avoiding single points of failure on the cloud storage and improving evidence availability.

Following by the advantages of BCoT conjunction, [83], [84] provided secure identity management solutions which allow cloud service providers to autonomously control and authenticate user identity in BCoT. Blockchain is combined with virtual clouds to support identity verification in a fashion there is no prior requirements on trust between cloud users and cloud providers. In such scenarios, blockchain is the best candidate for building a flexible and secure identity management mechanism on IoT cloud, which would be useful to various BCoT domains. On the other side, data management is also critical in interconnected Cloud of Things where IoT data is enormous and thus requires careful management for data privacy objectives. Motivated by this, the work [85] presented a blockchain-based data protection mechanism which can prevent effectively inappropriate IoT data movement due to malicious tampering during Virtual Machine (VM) migration on cloud computing. Blockchain provides a middle layer

which enables to perform validation on IoT migration request to cloud providers, aiming to detect unintended migration and data attack potentials. In the same direction, a Mchain construction method is applied to integrity evaluation on VM measurements data [86]. In this architecture, a two-layer blockchain network, which includes a data validation layer and a PoW task layer, is integrated with IaaS cloud to enhance system integrity. The implementation suggests that blockchain has potentials to help Cloud of Things overcome controllability and performance in terms of low system overhead and high data integrity [87].

In general, such above BCoT platforms are based on a single cloud and may be enough for some applications. However, with complex IoT systems which require huge network resources to serve numerous IoT users, inter-cloud BCoT integration would be more efficient and convenient [20]. As a result, BCoT architectures have been extended to multi-cloud models for complex collaborative scenarios [88], [89]. As an example, a BCoT framework was proposed on a joint cloud collaboration environment where multiple clouds are interconnected securely by a peer-to-peer ledge network [90]. The proposed scheme contains three tiers with an IoT sensor network, a federation of multiple clouds, and a service platform. Typically, the joint BCoT platform can offer many advantages over the schemes based on a single cloud. For instance, since IoT data at each area is stored in a private local cloud in the multi-cloud network, its data security is significantly improved. Further, the single cloud can offer instant services for IoT users through the private blockchain network, which also mitigates risks of malicious attacks on BCoT systems [91].

Moreover, [65] proposed a cloud federation model which enable distributed resource provisions using an individual cloud under the management of blockchain network. Importantly, blockchain allows distributed data control by data owners to improve security of cloud services and adjust privacy budget automatically by smart contracts. Besides, a BCoT model with micro-clouds was introduced by [92] using blockchain-enabled distributed ledgers. The authors pay special attention to build a joint cloud blockchain to enable secure decentralized collaborative governance services, i.e. storage, monitoring and resource management for suitable performance on lightweight computing nodes like IoT devices.

B. The conceptual BCoT architecture

Motivated by extensive literature review, we propose a conceptual BCoT architecture as shown in Fig. 8, including three main layers: IoT layer, cloud blockchain layer and application layer. Details of each layer and the general concept will be presented as the following.

1) IoT layer: IoT devices are responsible to harvest data from local environments and transmit wirelessly it to nearby gateways such as base station, router or wireless access point. An IoT device holds a blockchain account (like a wallet in Bitcoin) which allows it to join the blockchain network to perform transactions (i.e. offloading data) and interactions with cloud services. Specially, each resource-limited IoT device may act as a lightweight node that can participate in blockchain consensus through validation on hash values without keeping the whole blockchain data. This will encourage more low-resource IoT devices to engage in blockchain management processes, improve decentralization of the scalable BCoT network and solve the issues of unmanageable data volume and blockchain bloat [79]. Meanwhile, for IoT devices with relatively large resources such as computers or powerful smartphones, they have enough capacities to serve other lightweight IoT sensors and maintain full blockchain. In addition to cloud communication, IoT devices can interact each other through IoT gateways to achieve corporative communication (i.e. device to device (D2D) communication in collaborative networks) under the management of the cloud blockchain network. Such a hybrid communication concept offers highly flexible services for IoT users in a secure and efficient manner.

2) Cloud blockchain layer: This plays as a middleware between the IoT network and industrial applications in the BCoT architecture. For a generic architecture, we pay attention to a blockchain platform with multiple clouds, but it also reflects comprehensively technical aspects of a single-cloud BCoT architecture. This model exhibits two merits: 1) ensuring highly secure network management via blockchain and 2) providing on-demand and reliable computing services for large-scale IoT applications. The integrated cloud blockchain layer consists of blockchain services and cloud computing services.

- *Blockchain services:* The main purpose of blockchain in the proposed architecture is to provide secure network management. The blockchain network is deployed and hosted on a cloud platform as Blockchain as a Service (BaaS). In particular, BaaS can offer a number of blockchain-enabled services to support IoT applications.

- Shared ledger: It represents the database that is shared and distributed among BCoT members (i.e. IoT users, cloud nodes and blockchain entities). The shared ledger records transactions, such as information exchange or data sharing among IoT devices and cloud. It enables industrial networks where cloud users can control and verify their own transactions when communicating with blockchain cloud.
- Consensus: It provides verification services on user transactions by using consensus mechanisms such as PoW, PoS run by a network of miners. This service is highly necessary for BCoT in improving blockchain consistency and ensuring high security for the system. Interestingly, IoT users can use their virtual cloud machines to join the consensus process in order to receive rewards as a result of their efforts (i.e. cryptocurrency in Bitcoin).
- Shared contract: BCoT also offer smart contract services to applications. With its self-executing and independent features, smart contracts are highly beneficial to build business logic and trust in the BCoT system. Furthermore, smart contracts provide security services on user access authentication or data sharing verification once the IoT peer nodes perform transactions, which also supports to maintain security over the cloud blockchain.

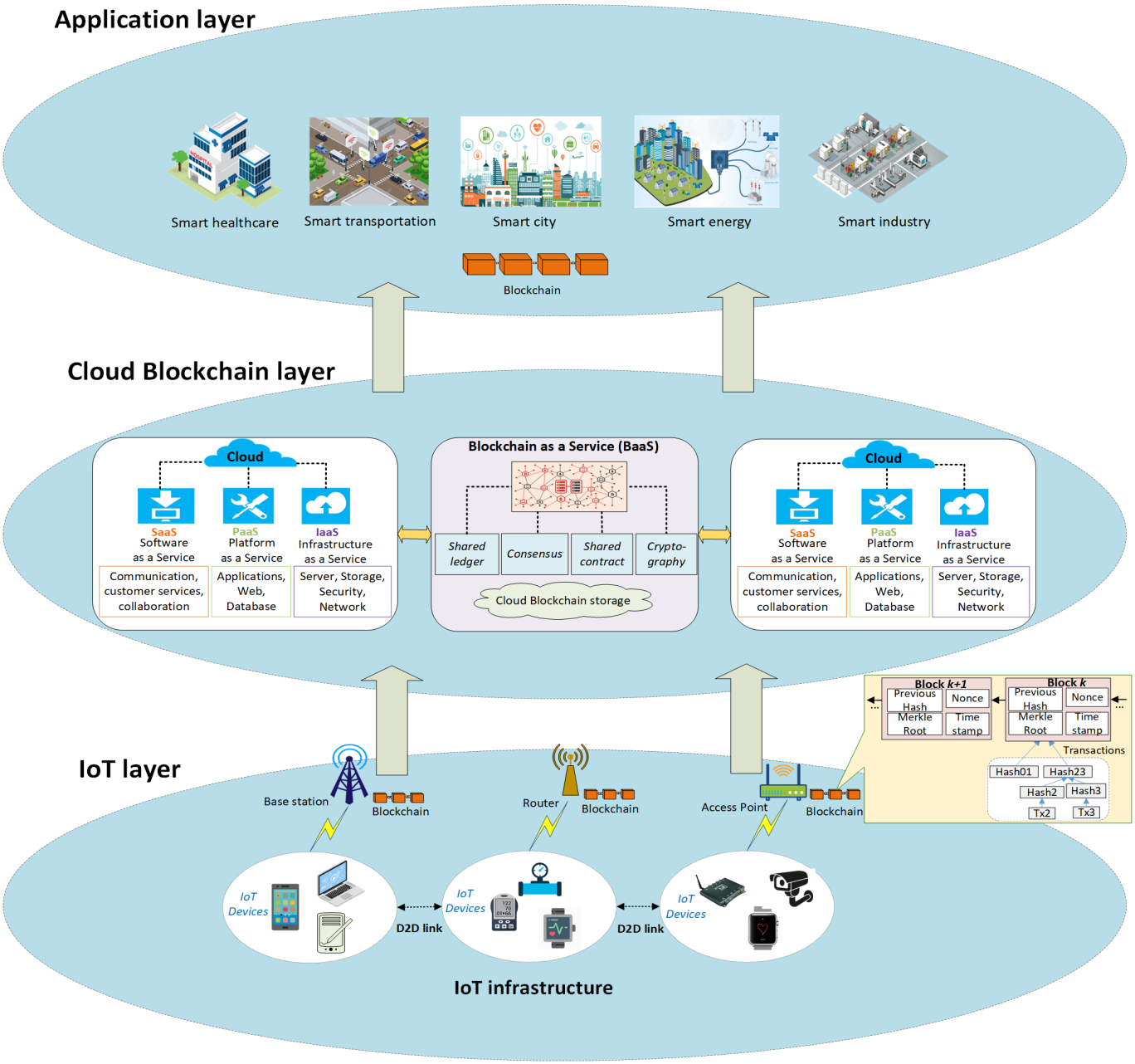

Fig. 8: The conceptual BCoT architecture.

- Cryptography: This is responsible to provide public-key cryptography to secure all information and storage of data among IoT and cloud entities. Digital signatures ensure any data being recorded in blockchain is true and untampered with, and this improves immutability and security for user transactions.

In addition to such services, BaaS also offers cloud blockchain storage. The decentralized cloud storage based on blockchain can be built on the cloud platform. Blockchain-based storage manages IoT data through its hash values and implements verification periodically to detect any data modification potentials. For example, InterPlanetary File System (IPFS) [93] is a blockchain-based storage system which is now available on cloud, allowing to store securely among storage nodes. This has also been proven to solve effectively data storage issues brought by centralized cloud models in terms of data leakage and storage management.

- *Cloud computing services:* In the BCoT architecture, cloud computing uses its full services to support applications, including Software as a Service (SaaS), Infrastructure as a Service (IaaS) and Platform as a Service (PaaS). Data aggregated by IoT gateways will be received by cloud servers and kept in the cloud blockchain storage. The cloud server also offers intelligent services on offloaded IoT data using available tools such as data mining or machine learning. IoT data can be stored off-chain in cloud database or on-chain in blockchain. On the other hand, multiple clouds can be incorporated to implement functionalities such as data sharing or collaborative system management. In this context, as a middle layer, blockchain layer plays an important role in

handling and controlling cloud interactions to facilitate cloud service delivery to IoT users and avoid conflicts among clouds.

Remark: Due to the large scope of P2P IoT network and distributed cloud, public blockchain such as Ethereum with smart contracts is highly recommended to build scalable BCoT platforms. Nowadays, many cloud platforms have integrated with blockchain to provide BCoT services for businesses, such as Amazon, Microsoft Azure or IBM. Details of BCoT platforms will be presented in the following sections.

3) Application layer: Many industrial applications can gain benefits from the BCoT integration in different areas where IoT scenarios are involved, like smart healthcare, smart transportation, smart city, smart energy, and smart industry. BCoT not only provides useful services to industrial applications, such as network management and QoS improvement but also guarantees security and privacy properties for applied domains. For example, in smart healthcare, BCoT can support data processing services thanks to computation ability of cloud, which can assist healthcare providers in analysing intelligently patient information for better medical care. In the meantime, network security of healthcare is ensured with blockchain which offers traceability and verification services during the medical data exchange and data processing. The application of BCoT integration and its benefits to IoT use case domains such as smart industry, smart energy, smart transportation will be extensively analyzed in the next section.

V. Research and Technology Development of BCoT

In this section, we will present recent advances of BCoT technology. The impacts of BCoT on a wide range of industrial applications are reviewed from the latest research results. Then, the benefits of BCoT paradigms in 5G-beyond networks are analysed. Final, we also survey recent BCoT developments with platforms, services, and research projects around blockchain, cloud computing and IoT technologies.

A. BCoT applications

The BCoT integration has led to the appearance of a new set of smart services and applications, which can bring substantial benefits to our daily life. We will provide readers with a summary of key BCoT applications across different scenarios, such as smart healthcare, smart city, smart transportation, and smart industry as shown in Fig. 9. In particular, we highlight the research findings of the state-of-the-art studies in the use of BCoT paradigms in such applications. Besides, main lessons learned from the review are also discussed.

1) Smart healthcare: Healthcare is an industrial sector where organizations and medical institutions provide healthcare services, medical equipment, medical insurance to facilitate healthcare delivery to patients. The adoption of BCoT models can offer great potentials to solve critical issues in terms of security and service efficiency, and thus is possible to advance medical services and transform current healthcare systems [94], [95], [96], [97]. The BCoT integration in healthcare promises to provide new smart services, including efficient health data sharing, healthcare data storage and secure system management, which will be summarized from the literature studies as the following.

1.1) Health data sharing

In the age of digital healthcare, a large amount of electronic medical records (EHRs) is created and shared among healthcare institutes and patients to support data analysis and achieve large-scale healthcare delivery. Specially, Cloud of Things enable efficient healthcare data sharing environments where EHRs can be processed and stored online on the cloud storage while users can use their mobile devices (i.e. smartphones) to access their medical information for health monitoring. This promises to offer on-demand healthcare services, save healthcare costs, and improve quality of experience [98]. However, healthcare data sharing based on such dynamic cloud IoT environments is always vulnerable to security and privacy risks due to attack potentials and the lack of trust between healthcare cloud providers, cloud storage, and users. This not only negatively affects healthcare operations, i.e. system interruption due to adversaries, but also results in serious data leakage issues. The innovative solutions enabled by blockchain can address effectively such challenges due to its immutable, secure, and trustworthy features.

The work [99] introduces a privacy-preserved data sharing scheme which is enabled by the conjunction of a tamper-proof consortium blockchain, cloud storage and medical IoT network. The proposed model is a three-layer architecture, with a data acquirement layer, a data storage layer, and a data sharing layer. In order to protect medical data, original electrical medical records (EMRs) are stored securely in the cloud under the management of smart contracts while data indexes are kept in blockchain. This ensures that EMRs cannot be modified or altered arbitrarily.

A user-centric health data sharing solution is also proposed in [100] using permissioned blockchain on a mobile cloud platform where health data from wearable sensors is synchronized to cloud for data sharing with healthcare providers and insurance institutions. Cloud blockchain is used for three key purposes, consisting of storing hashed data entry for integrity protection, processing data access from external request for permission management, and implementing access control for user verification. In this context, the cloud server is configured with a Fabric client to interact with blockchain network peers so that distributed peers can perform verification on transaction requests for data privacy guarantees on cloud.

Furthermore, to better preserve the privacy and availability of health data, the study in [101] presents a data sharing framework with fine-grained access control. The authors focus on a decentralized cloud system that combines a decentralized storage system interplanetary file system (IPFS), an Ethereum blockchain, and attribute-based encryption (ABE) technology. An access control design based on smart contract is also proposed to implement keyword search in decentralized cloud storage for sharing services, which improves data availability and trustworthiness of the data sharing system.

Although BCoT can help achieve secure data sharing, the storage of all health data on blockchain will slow down transaction operations and put sensitive patient information at risks of data leakage and sharing security concerns. Motivated by

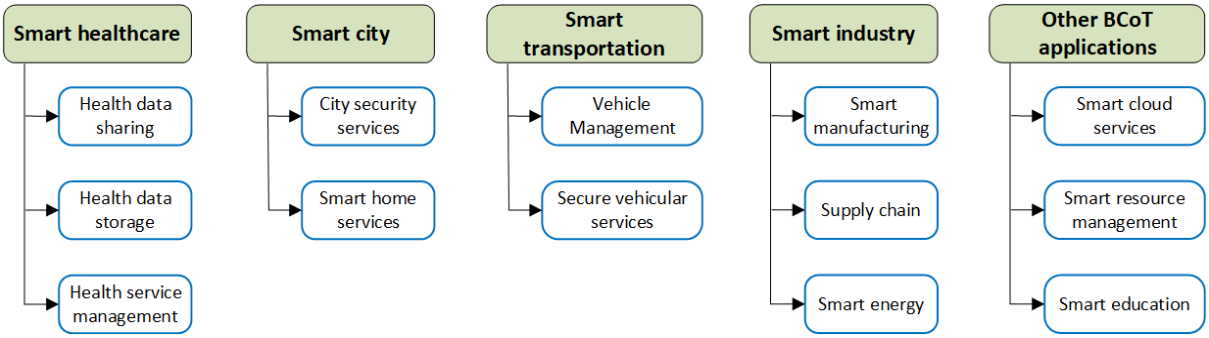

Fig. 9: BCoT application domains.

such challenges, [102] proposes a conceptual scheme for exchanging personal continuous dynamic health data using cloud storage and blockchain. In particular, large health datasets are encrypted and stored as off-the-chain in cloud storage, while only metadata (i.e. hash values) of raw data is kept in blockchain, which would overcome the size limitation of the large data storage in BCoT systems.

The authors in [103] propose a trust-less medical data sharing, called MeDShare, to enable data exchange among untrusted cloud service providers (CSP) using the blockchain. The work concentrates on access control design based on smart contracts to track access behaviours of data users and detect violation on data permissions. This facilitates healthcare collaboration between CSPs with the ability to provide provenance and auditing without any risks of data content exposure. However, access control issues associated with sensitive data in the cloud data pool remains unsolved. Therefore, the work [104] proposes secure cryptographic approaches (including encryption and digital signatures) to provide efficient access control which acts as a monitoring system layer to achieve data user authentication for cloud data sharing.

More interesting, in our recent work [105], a mobile cloud blockchain platform is proposed to implement dynamic EHRs sharing among healthcare providers and patients. Blockchain is integrated with cloud computing to manage user transactions for data access enabled by smart contracts. In particular, a decentralized storage IPFS run by blockchain is combined with cloud computing to make data sharing more efficient in terms of low latency, easy data management and improved data privacy, compared to centralized cloud architectures. IoT users (i.e. doctors or patients) can perform data sharing transactions via their mobile devices such as smartphones, which offers flexible data sharing services with high security. The concept of the proposed scheme can be seen in Fig. 10.

1.2) Health data storage

In conventional cloud IoT-enabled health systems, medical data is normally stored in cloud computing under the management of cloud service providers (CSP). However, CSP can be honest but curious about health records, which can lead to leakage risks of sensitive patient information. Moreover, the shift of EHRs to cloud may be also vulnerable to various types of attacks on data storage although cloud computing has its own security tools. Blockchain with its strong security capabilities can be a technical enabler to enhance the efficiency and security of current health data storage.

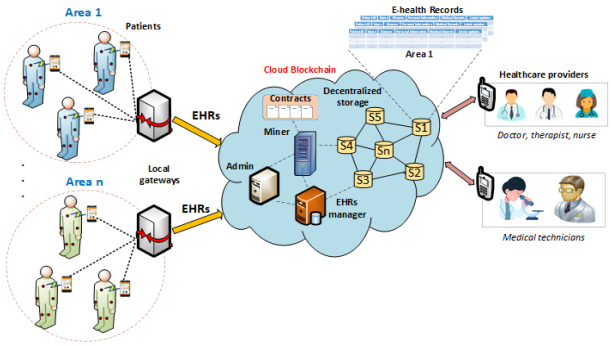

Fig. 10: A smart e-health data sharing system [105]. The BCoT architecture consists of wearable sensor network, cloud blockchain network and medical users. E-health data collected from IoT sensor devices are transmitted to the cloud and stored securely in decentralized cloud storage enabled by blockchain. Each mobile user has a blockchain account to join the BCoT network to perform transactions for data request which will be verified by smart contracts on clouds.

In [106], blockchain is utilized to design a privacy-preserved platform for healthcare data in cloud. Encrypted health records are stored in cloud blockchain under the control of smart contracts. By using blockchain, the system provides the full data ownership ability to patients and data users. Vulnerabilities regarding data preservation are addressed effectively by using cryptographic functions along with blockchain, improving integrity, accountability, and security for cloud data storage. Similarly, the work [107] introduces a secure cloud-based EHR system on blockchain with five entities: key generation centre, hospitals, patients, medical clouds, and data consumers like insurance company. In this network, medical data is stored in the blockchain associated with a complete copy of the timestamp, consequently increasing the integrity and traceability of healthcare records. The work in [108] integrates the medical data into the infrastructure of cloud blockchain called Blockcloud. Blockchain has distributed ledger where encrypted medicine data transactions are stored on cloud storage as a blockchain entity. Any modifications on medical records in cloud storage will be identified by blockchain via the P2P network. This concept also eliminates the requirement of the third-party for data storage management.

In [109], a modified BCoT scheme is proposed for decentralized health data privacy. The architecture consists of overlay network, cloud storage servers, healthcare providers, smart contracts and patients. Specially, blockchain is interconnected with cloud storage via a P2P network where each cloud storage

keeps medical records into blocks and the hash value of these blocks is stored in blockchain. This makes any changes in data possible to be easily traced. A double encryption scheme is also proposed to protect data against attackers and potential threats.

1.3) Healthcare service management

Blockchain is a decentralized and responsible mechanism which can facilitate healthcare services. In fact, by combining blockchain with Cloud of Things, the BCoT paradigm may offer unprecedented breakthroughs with new smart medical services, such as decentralized healthcare, secure user management or medical operation control [110].

In [111], a secure cloud-assisted e-health system based on blockchain is proposed to protect the operation of outsourcing EHRs among medical users. This can be done by an Ethereum blockchain platform to manage user transactions without requiring any trusted entity. EHRs generated from doctors in a treatment period can be integrated with blockchain transactions in a tamper-proof manner, and data integrity and correctness are ensured by security of Ethereum.

The study in [112] presents a healthcare remedy evaluation system, called CORUS, by utilizing blockchain-enabled crowdsourcing on cloud computing. The decentralized replication of blockchain can improve the information credibility and the quality of crowdsourcing systems. Further, blockchain can attract more participants to provide with credible information through a reward mechanism.

Recently, a healthcare project is implemented in Peru using the BCoT platform for purchase management in private health sector [113]. In this project, blockchain hosted inside the Amazon cloud is used to organize a secure communication network of purchasing manager, the supplier and the transporter. Sensor data will be authorized by mart contracts available on blockchain to avoid data alternation potentials.

Meanwhile, the authors in [114] highlight the efficiency of BCoT models in health monitoring services that are enabled by IoT devices, cloud computing and blockchain. Cloud connectivity offers substantial medical computing services, such as storage and intelligent computation. Blockchain can help overcome security challenges related to untrusted healthcare delivery environments.

In a recent work [115], we also introduce a conceptual BCoT framework for health diagnosis and monitoring. In particular, we integrate the data management system with a data sharing framework in a mobile blockchain network. Data is ensured security through an access control layer managed by smart contracts for access verification and data integrity.

1.4) Lessons learned

The main lessons acquired from the review of BCoT applications in healthcare are highlighted in the following.

- BCoT can achieve secure data sharing on cloud IoT-enabled healthcare networks where blockchain and cloud play a significant role in controlling user access and implementing data sharing. Smart contracts available on blockchain are particularly useful to track automatically transactions and implement access verification which ensures reliability and security for untrusted healthcare environments. BCoT paradigms therefore can facilitate healthcare collaboration between medical users and healthcare institutions with the ability to provide high data privacy and security.
- The integration of blockchain in cloud computing significantly improves security for cloud healthcare storage services. Cloud storage acts as a peer in the P2P network under the management of blockchain. In this context, original health data can be encrypted and kept in cloud storage, while metadata (i.e. hash values) of such data records is stored in blockchain, which enables data traceability and detects easily data modification threats on cloud.
- BCoT can offer innovative healthcare services with high security and efficiency. BCoT has the potentials to improve the quality of medical services such as health monitoring, patient diagnosis or healthcare remedy evaluation. Therefore, the use of BCoT models in healthcare is possible to transform healthcare delivery to achieve better quality of user experience and system security.

2) Smart city: With recent advances of cloud computing and IoT technology, smart city has been emerged as a new paradigm to dynamically exploit the resources in cities from ubiquitous devices and provide a wide range of services for citizens. Smart cities involve a variety of components, including ubiquitous IoT devices, heterogeneous networks, large-scale data storage, and powerful processing centres such as cloud computing for service provisions. Despite the potential vision of smart cities, how to provide smart city services with high efficiency and security remains a challenging problem. In this scenario, BCoT can be a promising candidate to empower smart city services by using attractive technical features of cloud computing and blockchain. A number of recently proposed solutions suggest to adopt BCoT architectures to enable ubiquitous connectivity between citizens and industrial applications for smart cities. We summarize recent research efforts in the adoption of BCoT in smart cities via two main services: security services for smart city and smart home services.

2.1) Security services for smart city

A smart city refers to the intelligent aggregation and acquisition of all kinds of data created in an integrated smart city network of citizens, computing servers, system management and ubiquitous devices. Due to the ubiquitous nature of data-based services, smart city architectures remain security bottlenecks such as privacy, integrity, trust, and so on [116]. BCoT with high security capabilities brought by blockchain promises to help overcome such challenges as well as offer new smart city services.

The work [117] introduces a decentralized big data integrity auditing framework in cloud environments for smart cities. The proposed architecture consists of two main entities: data owners and cloud service providers (CSPs). An innovative blockchain instantiation named the data auditing blockchain (DAB) is proposed to investigate auditing requests between users and CSPs to verify data integrity. In this context, blockchain is used to build a decentralized auditing architecture for ensuring high stability and reliability of the whole system without the requirement of third party auditors.

The study [118] considers an authorization and delegation architecture for the cloud IoT based on blockchain in smart city projects. The mechanism is conducted in a single smart contract which enables access control functionalities to ensure trustfulness and auditing for operations between IoT devices, cloud and data users.

Furthermore, blockchain is adopted in [119] to build an IoT-based smart city architecture which includes three main layers: smart block, P2P network and cloud. Since blockchain is inefficiently for a large number of network nodes, i.e. IoT devices in smart city, the proposed scheme suggests a lightweight blockchain with low computation and resource demands. All communications between IoT devices, cloud storage and P2P nodes are tagged as transactions which are recorded and stored securely on blockchain in a tamper-proof manner. The BCoT architecture for smart city is possible to preserve five main cryptographic primitives, including authenticity, availability integrity, confidentiality and non-repudiation.

Meanwhile, a blockchain-based infrastructure is proposed in [120] to support secure smart contract services for sharing economy in smart cities. Multimedia payload from IoT devices is offloaded and stored securely in distributed IPFS-based cloud repositories as immutable ledgers. Specially, the scheme also offers a sustainable incentive mechanism which can enable cyber-physical sharing economy services via IoT data. Smart contracts are also adopted to achieve spatio-temporal services without a central authentication authority.

2.2) Smart home services

In the context with smart cities, home automation gives shape to a smart home which is the main feature of a smart city. A smart home is a network of IoT devices configured with automated devices, intelligent sensors and detectors, which will collect information from the environment to be processed by a control server such as a computer or a cloud computing platform. Despite many potentials to benefit citizens, smart homes remain unsolved issues in terms of security, threats, attacks, and data privacy. BCoT run by blockchain that owns distributed, secure and private properties would be the promising solution to these security issues [121].

The work in [122] propose a smart home architecture using a BCoT model which includes three main tiers: cloud storage, overlay (blockchain-based P2P network), and smart home. Resourceful devices act as blockchain miners is responsible to handle transactions within the smart home and ensure security objectives in terms of confidentiality, integrity, and availability. The storage of data within smart home is implemented by cloud computing under the management of blockchain miners through a transaction authentication process which enables high security for smart home operations.

In [123], a secure and efficient IoT smart home architecture is proposed by taking advantage of cloud computing and blockchain technology. The general structures contain four components, namely smart home layer, blockchain network, cloud computing, and service layer. Blockchain with its decentralized nature is integrated in distributed cloud storage for data usage traceability. Besides, it also serves processing services and makes the transaction copy of the collected user data from smart home. Shared key policies between device and blockchain miners are implemented on blockchain to achieve authorization for smart home, and availability can be ensured by acceptable transactions between IoT devices and miners. Moreover, the study in [124] also presents a conceptual access control scheme for smart home where private blockchain is used to store records of user transactions and large-size access data is stored in off-chain storage, such as cloud storage.

2.3) Lessons learned

The main lessons acquired from the review of BCoT applications in smart city are highlighted in the following.

- BCoT can offer advanced security services for smart city applications. Cloud computing is capable of providing powerful computing capacities to handle large data streams from ubiquitous IoT devices to offer real-time applications for citizens. Meanwhile, with high security properties, blockchain proves its high efficiency in controlling smart city operations in a distributed and secure manner. The integration of blockchain and Cloud of Things thus transforms smart city architectures to overcome challenges in terms of security and system performance.
- As a significant component of smart city, smart home also gains benefits from the BCoT integration. BCoT can enable intelligent services, such as user monitoring, home management and access control in smart home scenarios. Specially, blockchain can be integrated with distributed cloud computing to make data storage and transaction processing more flexible and secure among IoT devices, home owner and external users.

3) Smart transportation: With the rapid development of modern sensing, communicating, computing technologies, recent years have witnessed tremendous growth in intelligent transportation systems (ITS), which impose significant impacts on various aspects of our lives with smarter transport facilities and vehicles as well as better transport services. Smart transportation is regarded as a key IoT application which refers to the integrated architectures of communication technologies and vehicular services in transportation systems. One critical issue in smart transportation is security risks resulted by dynamic vehicle-to-vehicle (V2V) communication in untrusted vehicular environments and reliance on centralized network authorities. BCoT has the potential to help establish a secured, trusted and decentralized ITS ecosystem. The combination of cloud computing with limitless data management capabilities and blockchain with high security features is able to enhance security and quality of service for smart transportation. Based on the literature review in the field, we categorize BCoT applications in smart transportation into two main groups: vehicular communication management and secure vehicular services, which will be summarized as the following.

3.1) Vehicular Communication Management

To achieve efficient and secure vehicular communication, BCoT can offer advanced solutions by combining cloud computing and blockchain in vehicular networks.

The work [125] proposes a collaboration network of multiple vehicle clouds where blockchain is applied to establish a coordination scheme. Vehicles from different car manufacturers can achieve efficient interconnection through their private

cloud based on a decentralized mechanism which enables service management, value exchange and collaborative trust within the vehicle-to-vehicle (V2V) communication network. Blockchain is adopted to support peer-to-peer collaboration among different clouds of vehicles with high security levels.

The authors in [126] introduce an electric vehicles cloud and edge (EVCE) computing network paradigm including seamless communications among heterogeneous vehicular contexts to aggregate distributed electric vehicles (EVs) so as to establish a common resource pool for collaborative utilization. Blockchain is used in information and energy interaction processes to achieve robust security protection. Specially, in such a context, blockchain-inspired data coins and energy coins are introduced as new cryptocurrency for vehicular applications. During information and energy interactions, vehicular records are encrypted and appended into the blocks by a consensus mechanism on consortium blockchain.

In [127], a distributed blockchain cloud architecture is proposed to preserve privacy of vehicle drivers with on-demand and low-cost access in vehicular ad-hoc networks (VANETs). To solve issues related to limitations of storage, computation and spectrum bandwidth in VANETs, a cloud computational hierarchical architecture is proposed with three interconnected cloud platforms, consisting of vehicular cloud, road side cloud and central cloud. The joint cloud network is interconnected securely with vehicles, service providers through a P2P network run by lockchain which enables the vehicular ecosystem to be resistant to cyber-attacks and privacy bottlenecks.

Meanwhile, the study [128] proposes a security architecture of VANET based on blockchain and edge-cloud computing. The architecture consists of three main layers, namely perception layer with a network of vehicles, edge computing layer and service layer as illustrated in Fig. 11. Here, the service layer is established by the integration of cloud computing and blockchain to build a secure decentralized vehicular management architecture. Therefore, cloud-based huge data storage and blockchain-based data privacy are ensured for efficient and secure vehicular communication [129].

3.2) Secure vehicular services

BCoT paradigms have been extensively adopted to improve vehicular services with better performances in terms of security and efficiency.

In [130], a BCoT architecture is developed to build a vehicular ecosystem where smart vehicles, equipment manufacturers and cloud storage providers can communicate together. The system operates under the management of a public blockchain which is possible to protect the privacy of users and to increase the security of the vehicular network. Two applications including wireless remote software updates and dynamic vehicle insurance fees are considered to demonstrate the efficiency of the architecture.

The authors in [131] consider the privacy issues of carpooling services which are defined as an approach to enable passengers to share a vehicle to reduce traveling time, vehicle carbon emissions and traffic congestion on the road. To achieve high security and privacy of the service, they propose an efficient and privacy-preserved scheme by using blockchain-enabled vehicular fog computing. A private blockchain is

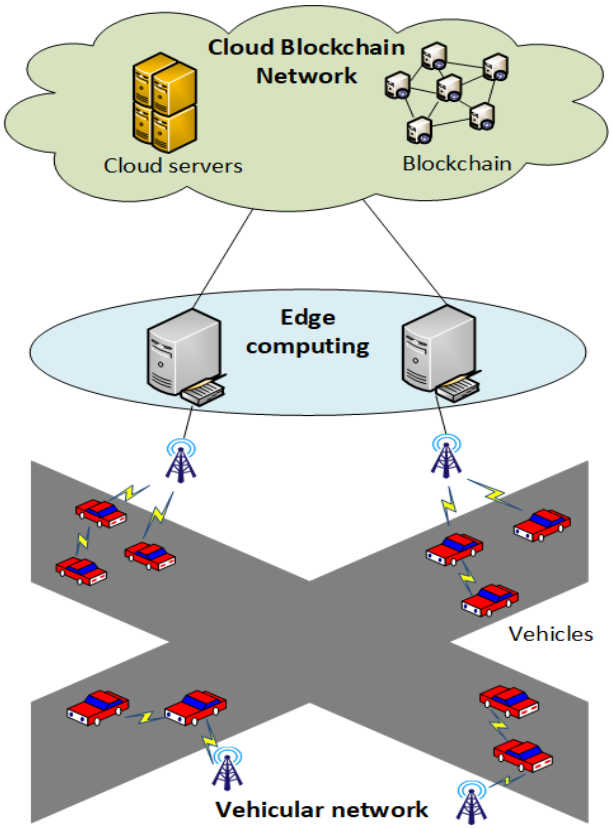

Fig. 11: Blockchain and cloud for security of VANET system [127].

constructed and hosted by road-side units (RSUs) to record immutably carpooling transactions. Particularly, carpooling data is encrypted and kept at the cloud server, while its hash value is stored on the private blockchain, which enables data traceability and reliability.

The work [132] uses the BCoT model to build a mechanism of task scheduling in a vehicular cloud computing environment. An autonomous vehicular cloud (AVC) ecosystem is established where non-repudiation of task execution between task senders and task runners (vehicles) is guaranteed by secure transaction management of blockchain. Smart contracts are created by task senders and run on Ethereum blockchain to control the task execution process.

Meanwhile, the study [133] presents a fine-grained transportation prototype for insurance services enabled by the blockchain and Cloud of Things. The system consists of two main parts, namely an IoT based data collection and processing scheme for driving behaviour analytics and a collaborative blockchain network of Ethereum and Hyperledger Fabric platform for vehicular operation management. Smart contracts are utilized along with built-in tokens to facilitate the automatic payment operations and the incentive mechanism which encourages safer driving and promotes fairness among vehicle drivers.

Furthermore, security for vehicular IoT services has become a critical challenge. VANET is featured with high mobility and variability, and malicious vehicles or misbehaviours are unavoidable in large-scale vehicular scenarios. Incredible messages by malicious vehicles can greatly endanger the

transportation system and therefore, it is vitally important that VANET needs to ensure security for IoT environment where vehicular service related messages should be immutable, credible and authentic. Motivated by this, the work [134] proposes a blockchain-based security framework to support vehicular IoT services, i.e., real-time cloud-based video report and trust management on vehicular messages. Software-defined network (SDN) architecture is incorporated into the VANET to enable global information collection and network management. A blockchain platform is employed to build a semi-decentralized trust management architecture in which encrypted videos or messages are uploaded to the cloud for large storage while trusted traffic information is stored securely in the blockchain.

3.3) Lessons learned

The main lessons acquired from the review of BCoT applications in smart transportation are highlighted in the following.

- BCoT paradigms can offer advanced solutions by combining cloud computing and blockchain in vehicular networks to achieve efficient and secure vehicular communication. Blockchain can create secure peer-to-peer network environments to enable limitless communications among ubiquitous vehicles for service management, value exchange and collaborative trust.
- CoT also enable a new set of vehicular services with better efficiency and security. The combination of autonomous vehicular cloud and blockchain opens up new opportunities to facilitate vehicular IoT services, from task scheduling, data carpooling, insurance management to vehicular report and trust control services, which promise to transform intelligent transportation systems.

4) Smart industry: Cloud of Things (CoT) have been widely adopted in smart industry for industrial and manufacturing applications such as manufacturing automation, smart factory and supply chain management. While the CoT-based smart industry enables on-demand access to manufacturing resources and offers intelligent services to customers, a secure industry architecture is required to ensure system trustfulness and data privacy for transactions among users and industrial manufacturing entities. Blockchain has emerged as an enabling technology enabled by the decentralized P2P network structure to drive smart industries, and the convergence of Cloud of Things and blockchain as a BCoT paradigm promises to empower industry ecosystems with enhanced security and improved industrial operation efficiency. There is a vast body of research works in the combination of BCoT in smart industry and we can categorize them into three areas: smart manufacturing, smart energy, and smart supply chain.

4.1) Smart manufacturing

Smart manufacturing is a broad category of manufacturing that employs cloud manufacturing, IoT enabled technologies and service-oriented manufacturing, which benefit the manufacturing industry. However, all existing paradigms still face the main problem related to centralized industrial network and third part-based authority. In a nutshell, centralized manufacturing architectures exist limitations with low flexibility, efficiency, and security. The use of BCoT in manufacturing systems can be a promising solution to overcome such critical challenges with the support of cloud computing and blockchain. BCoT is possible to enhance and optimize manufacturing processes and reduce operation costs. Besides, it also offers efficient security services for trust and privacy establishment among different manufacturing enterprises [136].

In [135], a distributed P2P network architecture named BCmfg is proposed with five key layers, namely resource layer, perception layer, manufacturing layer, infrastructure layer and application layer. Blockchain is integrated in the manufacturing industry to facilitate cloud manufacturing and establish a new trustable platform as blockchain cloud manufacturing. Service providers and customers can share data and information over the cloud blockchain network which helps improve the security of industry system. Smart contracts act as agreements between the end users and the service providers to provide on-demand manufacturing services.

The work [137] introduces a decentralized framework called BPIIoT for industrial IoT based on blockchain. The BPIIoT platform is regarded as a technical enabler for cloud-based manufacturing (CBM) which offers ubiquitous and on-demand network access to manufacturing resources. Blockchain is deployed to establish a peer-to-peer network for BPIIoT in which smart contracts are deployed. Here, the smart contracts work as agreements between the service consumers and the manufacturing resources to provide on-demand manufacturing services. The proposed BPIIoT model can allow to integrate legacy shop floor equipment into the cloud environment and develop peer-to-peer manufacturing applications with high security, auditability and scalability.

4.2) Smart supply chain

In addition to manufacturing applications, BCoT is also beneficial to industrial supply chain that is the key component in the vertical smart industry ecosystem. Indeed, BCoT with high decentralized and secure natures of blockchain can ensure faster and more efficient corporation between companies and manufacturers in supply chain and logistic activities [138]. Besides, it also enables secure support planning, scheduling, and monitoring supply chain operations.

For example, the work in [139] investigates the use of blockchain for transaction processing to provide different cloud-blockchain platforms for supply chain applications. Blockchain systems are divided into three categories, including private versus public, centralized versus decentralized and peer-to-peer cloud-based systems. Cloud computing can offer a number of flexible solutions for blockchain-based supply chain, from a single repository for the blockchain to multiple peer-to-peer capabilities with broad accessibility. Blockchain ensures trust among companies and businesses during supply chain operations via consensus mechanisms and smart contracts.

4.3) Smart energy

With the increasing demands of energy usage to support industrial and manufacturing operations, smart energy continues to play an integral part in industry ecosystems. The overall purpose of the energy system is to provide energy services to customers and companies, in a sustainable, reliable, and cost efficient manner. Information and communication technology (ICT) will be an enabler in the transition of electricity, gas and heating grids into the smart energy system. In such a context,

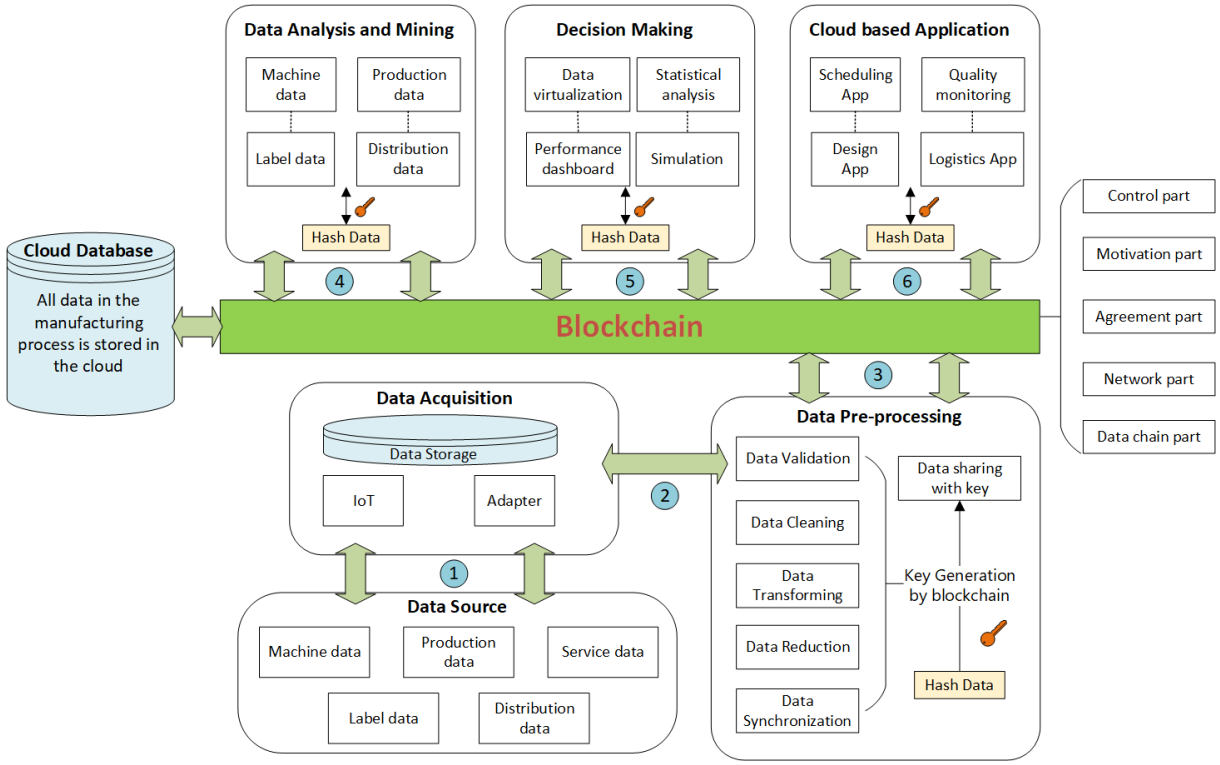

Fig. 12: The blockchain cloud manufacturing system [135].

BCoT models empowered by blockchain have emerged as a promising technique not only to realize trusted, reliable and efficient smart energy network but also to improve security and privacy of energy exchange and transmission.

The work [140] considers the potential of cloud-blockchain technologies for decentralized operations in energy internet environments. Centralized energy management systems (EMS) tend to be inefficient to work well with a large quantity of prosumers and thus, a decentralized architecture based on blockchain is necessary to achieve high quality of services for the decentralized institutions of various energy entities. Blockchain can integrate with cloud computing to offer effective methods for information sharing and model updating in cloud-based EMS platforms. Specially, cloud computing operations for energy management are optimized and ensured high security with a decentralized verification mechanism which is made by blockchain-based consensus among energy users.

In [141], a blockchain-based architecture is proposed to manage the operation of crowdsourced energy systems (CES), enabling P2P energy trading at the distribution level, where ubiquitous distribution-level asset owners can trade with each other. Blockchain can support seamless P2P energy trading between individual prosumers and the energy entities and allow the system operator to manage the network users. The platform is implemented by the IBM Hyperledger Fabric network deployed in cloud to offer blockchain services. Moreover, smart contracts are used to run the pricing mechanism and control energy trading transactions and crowdsources.

Meanwhile, the work in [142] proposes an intelligent energy aware resource management in cloud datacentre (DC) using the blockchain. The authors pay attention to the cost minimization issues in cloud DCs and how to reduce the total cost of energy consumption from the traditional power grid, request scheduling cost, and request migration in DCs. With the support of blockchain, the enery management scheme does not require any scheduler, reducing extra energy cost and increasing the robustness of DCs. Smart contracts are also employed and stored in each DC to verify transactions from request migration to the DC, which enables access control and high security for energy centres without the need of any centralized controller.

4.4) Lessons learned

The main lessons acquired from the review of BCoT applications in smart industry are highlighted in the following.

- BCoT demonstrates its potentials in the improvement of smart industry for better efficient manufacturing, lower operational costs and minimum management efforts through the use of controlling capabilities of blockchain and service support of cloud computing.
- BCoT with blockchain as a middle communication layer can enable faster and more efficient corporation between companies, manufacturers and users in supply chain and logistic activities. Security and information privacy during supply chain operations can also be ensured by consensus mechanisms over the peer-to-peer network enabled by cloud-blockchain integration.
- BCoT architectures can empower energy systems which are regarded as a key component of smart industry. Blockchain has potentials to improve security and privacy of energy exchange and transmission, while cloud computing offers storage and management services as well as supports blockchain in achieving decentralized energy operations.

5) Other BCoT applications: The application of BCoT paradigms has been investigated in other scenarios, including smart cloud services, smart resource management and smart education.

5.1) Smart cloud services

Cloud computing offers a diverse range of outsourcing services, including storage and computation to serve individuals and enterprises. Basically, outsourcing services usually include online payment and security issues. However, most traditional service solutions have to rely on a trusted third-party to realize fairness to complete payments. For example, Google cloud platform offers a variety of computing services such as data storage and computation, and the user registration and service usage needs a bank account created by a third party financial institution. This can lead to serious issues, such as network interruption when banking systems are out of service or data leakage caused by the third party. Therefore, the realization of secure and fair payment of outsourcing services is of paramount importance for cloud-based applications. In this regard, blockchain has emerged as a strong candidate to solve security issues of cloud services thanks to its distributed and immutable natures. The works [143], [144] introduce a blockchain based fair payment architecture for outsourcing services in cloud computing. The proposed system ensures to provide soundness and robust fairness capabilities by using a service management protocol run by blockchain. Fair payment can be achieved between users and outsourcing service providers on clouds through transactions which are stored and verified by blockchain without the involvement of any third party.

During the process of outsourcing data on clouds, when a user wants to delete the outsourced data, he sends a deletion command to the cloud server so that the server delete the data. However, the cloud server is semi-trusted and it may not delete the requested data honestly due to financial incentives. To solve this issue, the study in [145] presents a new publicly verifiable data deletion scheme for cloud computing enabled by blockchain, which not only supports public verification on deletion requests but also eliminates totally the need of trusted third parties. Blockchain offers fairness verification services which enable all users can authorize transactions for data deletion requests and control malicious behaviours on their cloud data with equal verification rights. This blockchain-base scheme helps reduce the dependence on cloud servers in user data management and makes the deletion operation much more transparent.

Meanwhile, the authors in [146] propose a Building Information Modeling (BIM) system model called bcBIM to address information security challenges in mobile cloud environments. Specially, blockchain is employed to facilitate BIM data audit for historical modifications of big data sharing. BIM data integrity and provenance are guaranteed by integrating blockchain in BIM database, and system management can be achieved by BIM cloud. The BIM model based on cloud blockchain promises to foster industrial applications, such as engineering machines and construction robots.

For data record management on clouds, [147] and [148] use blockchain to build decentralized cloud storage ecosystems for security improvements. Blockchain-based distributed storage is different from traditional cloud storage services because it utilizes the disk space of a network of computers and storage facilities to decentralize the database, which ensures that any data owners can verify and check data integrity via the P2P network on blockchain. This advanced storage concept also improves trustworthiness and data availability on cloud during data long-term preservation.

5.2) Smart resource management

Computing resource management for Cloud of Things in blockchain network is also attracting increasing attention. Many approaches have been proposed to enhance computation resources and security services for BCoT applications in various types of tasks such as real-time processing, resource-intensive applications, blockchain mining, and consensus process.

The work [149] introduces an optimal computing resource allocation based on an auction scheme for edge-cloud-enabled IoT in the blockchain network. A pure P2P computing resource trading system on clouds is built to establish computing resource trading between resource sellers and buyers. Meanwhile, a lightweight infrastructure of the PoW-based blockchains is proposed [150] so that the workload of mining process is offloaded to the cloud/fog for computation. The computation resource management in the blockchain consensus process is formulated as a two-stage Stackelberg game, where the profit of the cloud/fog providers (CFPs) and the utilities of individual miners are jointly optimized.

Further, the authors in [151] introduce a resource management system called Saranyu which adopts smart contracts to control tenant and service accounts as well as monitor resource usage in a cloud computing data center. Saranyu is capable of offering four different services: identity management, authentication, authorization on service resource exploitations, and charging. The strong security characteristics of blockchain such as non-repudiation, tamper-resistance and transaction verification can improve transparency and trustfulness in cloud tenant and service management.

5.3) Smart education

The application of BCoT to the education domain is still in its early stages. Only a small number of educational institutions have started to utilize BCoT technology. Most of current solutions use BCoT for the purpose of validating and securely sharing academic certificates and personal information of students as well as learning database of educational institutions [152].

For example, the study in [153] proposes an online identity verification system using blockchain to implement cloud educational collaboration. To achieve time authentication on transactions, blockchain is adopted to provide proofs of data content originality, which also maintains system integrity. Some case studies were conducted at Chuo University in Japan to verify the efficiency of the proposal. Additionally, blockchain ledgers and cloud computing are considered to support computer science education in [154]. A new decentralized P2P-cloud model is also proposed using Bitcoin and Torrent models to build proof-of-concept platforms to support service providers in education.

5.4) Lessons learned

The main lessons acquired from the review of above BCoT applications are highlighted in the following.

- The BCoT architecture has great potentials to transform cloud-based services with better efficiency and security levels. Blockchain can be involved in cloud management processes by autonomous consensus mechanisms and control capabilities of smart contracts, which ensure data integrity, data availability and trustfulness. Importantly, blockchain helps to build peer-to-peer architectures and integrate them in cloud platforms to enable decentralized cloud services with advantages over conventional cloud ecosystems in terms of no single points of failure for better system robustness and low communication overheads.
- BCoT also proves its benefits to network resource management with a wide range of services on real-time processing, resource-intensive applications, blockchain mining, and consensus process. With the support of BCoT and smart contracts available on blockchain, resource management systems can achieve high transparency, trustfulness and ensure robust access control in collaborative networks of resource providers and customers.
- Besides, BCoT can be useful to education management ecosystems. Blockchain ledgers and cloud computing can be combined to develop secure and trusted educational environments for promoting educational collaboration.

In summary, we list BCoT applications in the taxonomy Table III and Table IV to summarize the contributions and limitations of each reference work.

B. BCoT in 5G networks and beyond

The next generations of mobile network (5G and beyond) have revolutionized industry and society by providing an unimaginable level of innovation with a large number of advantages such as high data rate, low network latency, energy savings, reduced operational costs, higher system throughput and massive device connectivity. The conjunction of BCoT and 5G has the potential to drive evolution of scalable wireless networks, transform current IoT architectures, and improve security of cloud IoT applications with the support of the blockchain technology [155], [156], [157]. Fig. 13 depicts a generic BCoT architecture in 5G-beyond networks in which some advantages can be inherited from this innovative integration, such as improved network management and security services. We will highlight them in details as the following.

1) Network management: 5G offers a completely new vision of mobile networks to unify the management of IoT networks. In order to support various types of IoT applications, 5G relies on the concept of Network Slicing, which is the separation of multiple virtual networks operating on the same physical hardware [158]. It enables telecom operators to portion their networks for specific services and applications, such as smart home, smart factory or vehicular network. Network slicing is well supported by Network Softwarization as the key technological enabler which consists of Virtual Network Functions (VNFs) running in the cloud inside virtual machines or containers. Each network slice contains a set of VNFs

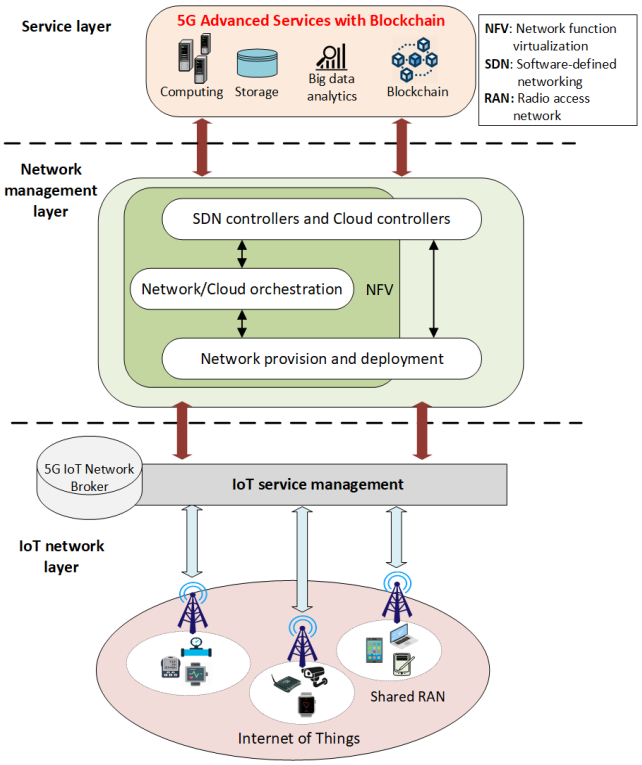

Fig. 13: The BCoT integration in 5G networks.

associated with physical network functions to enable network services based on the computing and storage capabilities of cloud infrastructure.

In this context, blockchain and cloud computing can bring great opportunities to 5G network management. For example, blockchain can be exploited to build reliable end-to-end network slices and allow network slide providers to manage their resources. The work of [157] uses blockchain for the dynamic control of the source reliability in vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communications in vehicular network slices. Moreover, blockchain has the potential to build efficient brokering mechanisms which are utilized by slice providers for managing slice deployment [159]. In particular, smart contracts are adopted to monitor resource usage by sub-slices and keep track of transactions and records on blockchain [160]. Blockchain may facilitate resource management in 5G network slice broker scenarios such as industrial IoT ecosystems [161]. Meanwhile, cloud infrastructures enabled by cloud technologies such as cloud-native applications, network functions virtualization (NFV), programmable networking, potentially improve 5G network slicing functions and capabilities. For instance, the study of [162] demonstrates that cloud-native designs can enable to establish life-cycle slice management and to create, orchestrate and optimize performances of network slices in terms of network load, utilization of allocated resources, end-to-end delay, and data throughput. Further, hierarchical edge cloud-based network slices can support service provisions with desired quality of service (QoS) and reduce the capacity burden of 5G optical mobile fronthaul network [163].

In addition to network slicing, Software Defined Networking (SDN) is a promising technology that helps to simplify 5G

TABLE III: Taxonomy of BCoT applications.

Category	Ref.	Use case	Blockchain platform	Main contributions	Limitations
Smart healthcare	[99]	EMRs sharing	Consortium blockchain	An EMRs sharing scheme to ensure data privacy on cloud.	The real prototype is not implemented between cloud, blockchain and medical users.
	[100]	Health data sharing	Permissioned blockchain	A user-centric health data sharing solution for cloud healthcare with a focus on scalability and data integrity evaluation.	Security issues on healthcare IoT devices, i.e. malicious attacks, are not considered.
	[101]	Data sharing, access control	Ethereum	A data sharing with access control in decentralized loud storage.	Issues on data confidentiality and access control latency are not discussed in detail.
	[102]	Data sharing	-	A lightweight data sharing scheme in cloud blockchain.	The real prototype is not investigated between cloud, blockchain and medical users.
	[103]	Trust-less data sharing	-	An access control mechanism to track data access behaviours of cloud providers.	Implementation results on access control efficiency is not investigated.
	[105]	E-health data sharing	Ethereum	A mobile cloud blockchain platform for e-health sharing with an access control design.	Data confidentiality and scalability are not considered in detail.
	[106]	healthcare data management	Ethereum	A privacy-preserved platform for data storage in cloud.	Comparisons between smart contract-based scheme and conventional schemes have been not done.
	[107]	Cloud data storage	-	A blockchain-based cloud storage scheme for data integrity and traceability.	Smart contract implementation on data storage has not been considered.
	[108]	Cloud data storage	-	A EMRs storage scheme on blockchain-based cloud.	Investigations on blockchain prototype has not been done.
	[109]	Security for EMRs storage	-	A security scheme for EMRs storage.	Real experiments on the proposed security scheme has not been done.
	[111]	Secure healthcare service	Ethereum	Secure cloud-assisted e-health system.	Smart contract design for service management has not been considered.
	[112]	Healthcare remedy service	-	A healthcare remedy evaluation system.	Performance for blockchain implementation on cloud has not been done.
	[113]	Medical supply chain	Hyperledger	Purchase management in private health sector.	Data privacy has not been considered.
	[114]	Health monitoring services	-	A concept of health monitoring services using BCoT approach.	Performance evaluation on the proposed scheme has not been done.
	[115]	Health diagnosis and assessment	Ethereum	A conceptual framework on health assessment and monitoring using cloud blockchain	System scalability and communication costs have been not considered.
Smart city	[117]	Data auditing	-	A decentralized data auditing framework on cloud for smart cities.	Smart contract design, experiment on security evaluation have not been done.
	[118]	Service authorization and delegation	Ethereum	An authorization and delegation scheme for BCoT-enabled smart city.	Privacy is not taken into consideration.
	[119]	Secure smart city architecture	Ethereum	A BCoT smart city platform for high security.	Access control for cloud storage has not been considered.
	[120]	Sharing economy services	Ethereum and Hyperledger	A blockchain-based infrastructure for secure sharing economy services.	Data privacy has not been analysed.
	[122]	Smart home services	-	A BCoT architecture for security and privacy in smart homes.	Blockchain implementation has not been done.
	[123]	Smart home services	-	A smart home architecture for security services.	Real blockchain implementation has not been investigated.

network design and management. It relies on software-based programming, enabling to define network policies managed by the SDN controller. SDN associated with NFV can implement network slicing which enables virtualization of physical networks. In this regard, cloud computing can be integrated with SDN and NFV in the 5G environment for fast chaining of the virtualized services which would improve QoS performance of mobile networks [164]. IoT devices can gain benefits from the integrated cloud-SDN architectures in network slices to support data analytics, data offloading and management with respect to device mobility. In particular, it is shown in [165] that the combination of access cloud and SDN plane to provide mobile services for machine-type communication (MTC) devices with low latency and better mobility management. Meanwhile, blockchain also proves its efficiency in managing large IoT data and improving mobile computation delivery in integration with SDN controllers at the edge of the mobile network [166]. In the future, the conjunction of blockchain and cloud computing technologies can help telecom operators to ensure reliable service provisions and solve critical IoT computing issues in 5G networks such as latency, scalability and system performance.

2) Security services: The new architectures and services emerged in 5G wireless networks have brought new challenges to security and privacy preservation [167]. Indeed, dynamic mobile communications between ubiquitous IoT devices, cloud data sharing on untrusted environments and the emergence of new intelligent attacks have become serious security issues for 5G mobile-based applications. In such scenarios, the blockchain technology which is able to perform transparent, trustful, and secure digital transactions with proof of rights and data ownership capabilities can be a very promising solution to overcome above security challenges. Besides, security strategies provided by cloud computing with SDN

TABLE IV: Taxonomy of BCoT applications (continued).

Category	Ref.	Use case	Blockchain platform	Main contributions	Limitations
Smart transportation	[125]	Vehicle collaboration	-	A joint cloud collaboration scheme between vehicle clouds based on blockchain	Blockchain implementation has not been done.
	[126]	Information and energy interactions	Consortium	An electric vehicles cloud and edge computing network paradigm for secure vehicular communication with blockchain.	Network performance has not been evaluated in experiments.
	[127]	Secure vehicular communication	-	A distributed vehicular network based on cloud blockchain for data privacy.	Blockchain implementation for the proposed approach has not been done.
	[128]	Secure vehicular communication	-	A multi-layer decentralized VANET architecture for secure vehicular communication.	Implementation to investigate the system efficiency is lacked.
	[130]	Secure vehicle services	-	A BCoT platform for secure vehicular services, i.e. remote software updates and vehicle insurance fees.	Blockchain and smart contract implementations have been not done.
	[131]	Carpooling services	Private blockchain	A privacy-preserving carpooling scheme using blockchain with cloud-fog computing.	Scalability of the proposed scheme has not been verified.
	[132]	Vehicular task scheduling	Ethereum	A strategy for task scheduling in autonomous vehicular cloud system.	The performance of the proposed framework has not been simulated.
	[133]	Fine-grained transportation insurance	Ethereum and Hyperledger	A fine-grained transportation scheme for insurance services on cloud blockchain.	Privacy issues in vehicular transactions is not taken into consideration.
	[134]	Vehicular IoT services	-	A blockchain-based security framework for vehicular IoT services.	Scalability of the proposed scheme and access control have not been verified.
Smart industry	[135]	Smart manufacturing	Ethereum	A blockchain cloud manufacturing system for secure manufacturing industry.	Access control to the data storage in cloud database has not been considered.
	[137]	Manufacturing platform	Ethereum	A decentralized framework for manufacturing applications with cloud blockchain.	The performance of the proposed framework has not been simulated.
	[139]	Supply chain	-	A conceptual cloud blockchain framework for supply chain.	BCoT implementation for supply chain scenarios has not been done.
	[140]	Smart energy	-	A cloud-blockchain scheme for decentralized operations in energy internet.	Only conceptual analysis is provided and simulation to evaluate the proposal is lacked.
	[141]	Smart grids	Hyperledger Fabric	A crowdsourced energy system for energy trading on cloud blockchain.	Scalability of the cloud-blockchain based solution in smart grids has not been considered.
	[142]	Smart energy	Ethereum	An intelligent energy aware resource management in cloud datacentre (DC) using blockchain.	Mining cost, privacy of energy data in cloud data centre have not been considered.
Cloud services	[143]	Smart payment	Ethereum	A blockchain based fair payment architecture named BCPay for outsourcing services.	Data privacy has been not investigated.
	[145]	Data delection	-	A new publicly verifiable data deletion scheme on cloud using blockchain.	The feasibility of the proposed model has not been investigated on real world cloud platforms.
	[149]	Resource management	-	An optimal computing resource allocation scheme on cloud blockchain in IoT.	Smart contracts for access control among resource users have not been investigated.
	[151]	Cloud service management	Ethereum	A service management system based on smart contracts for cloud resource provisions.	Data privacy on service exchanges has been not investigated.
	[153]	Smart education	-	An online identity verification system based on blockchain for educational collaboration.	Real implementation results have not been reported to verify the proposal.

and NFV can support secure and trusted mobile services in 5G networks [168].

As an example, blockchain can be used to achieve trust management for IoT services in SDN-based 5G mobile vehicular communication thanks to its decentralized and immutable characteristics [134]. With the support of the blockchain-based secure architecture, the 5G-VANET scheme can detect and prevent malicious access and threats to vehicular ecosystems hosted at the SDN controllers. Besides, it is proven that blockchain can support secure and energy aware key management for 5G network coded architectures [169] with the ability to reduce computational complexity and the communication overhead. The work in [170] also shows that blockchain and encrypted cloud storage can enable secure data sharing and privacy protection in 5G content-centric networks. Distributed immutable ledgers of blockchain can help achieve trust on mobile data communications and ensure both access control and privacy on IoT data, while cloud computing can offer security mechanisms, such as cryptographic primitives, to preserve cloud controllers against external attacks [171].

On the other side, authentication is also of paramount importance for 5G mobile services. Blockchain can work as a ledger of service for mobile systems where communications between service providers (i.e. cloud operators) and IoT users can be recorded immutably in a series of transactions, and all entities can be authenticated via their own public key certificate enabled by smart contracts [172]. Moreover, blockchain can be built on top the ultra-dense network to address security authentication issues in 5G [173]. Specially, the authors in [174], [175] apply blockchain to build a trusted authentication architecture for cloud radio access network (Cloud-RAN) in 5G era. They also show that the proposed schemes can address effectively network access authentication with trusted agreement among service providers and IoT users

with reduced operation costs and improved spectrum usage over Cloud-RAN based mobile networks.

C. Platforms, services and projects of BCoT

The integration of blockchain and Cloud of Things can lead to develop unprecedented architectures to enable smart services across IoT domains. In this section, we review the latest research efforts to integrated BCoT models with cloud blockchain storage platforms, cloud services for BCoT applications and research projects in BCoT scenarios.

1) Decentralized cloud blockchain storage: The data storage of traditional Cloud of Things applications have mainly relied on cloud computing which is a completely central environment. This centralized storage architecture shows a number of critical limitations, such as the lack of user control on IoT data as well as security and privacy concerns. Further, centralized cloud storage service providers charge a significant fee for their services. For example, Amazon cloud charges $23 a month for the storage service they provide, which may pose a burden on small cloud IoT projects. On the other hand, conventional blockchain seems to be very expensive for storing large amounts of IoT data on chain. In fact, blockchain platforms like Bitcoin are restricted data storage only one megabyte. To overcome such challenges, decentralized storage based on cloud blockchain would be a promising solution which offer highly flexible, secure, trustful and super cheap storage services for BCoT applications [101], [105].

In this regard, we survey the most popular decentralized storage platforms and summarize them in Table V. Key information of these platforms is also highlighted, and the open sources of software for ready usage are also released. With these advanced storage solutions, the BCoT applications do not rely on a central service provider, allowing users to store IoT data to a distributed set of storage nodes, i.e. computers, based on the peer-to-peer network on blockchain. In fact, many of these systems have proven their efficiency in IoT scenarios. For example, the decentralized IPFS [176] and Storj [177] storage platforms are applied in IoT systems on cloud blockchain [105], [147] and shows their efficiency in terms of low access latency and improved security levels, compared to traditional centralized storage solutions. Additionally, Swarm [180] works as the distributed data storage platform running on Ethereum which has the potential to manage and share securely IoT data against denial of service (DDOS) attacks and malicious access [184]. Recently, some cloud giants have launched initiatives to integrate decentralized storage for large-scale cloud blockchain deployments, such as IPFS storage on Amazon and Microsoft Azure clouds [105], [185], for secure and efficient data storage. These interesting integrations have the potentials to disrupt both blockchain and cloud computing worlds to enable new infrastructures for future BCoT applications.

2) Blockchain platforms with cloud computing: In BCoT ecosystems, blockchain can be regarded as a Blockchain-as-a-Service (BaaS) which is integrated with cloud computing to offer full IT services in order to help researchers and enterprises develop, verify and deploy blockchain for cloud IoT applications. Specially, BaaS platforms are capable of providing foundation architecture and technical support to ensure that BCoT systems can achieve robust and efficient operations. Nowadays, there is a large number of BaaS providers on commercial markets to enable customers to adopt services without worrying about infrastructure installation and system investment, which can accelerate their BCoT deployments.

Reviewing thoroughly the state-of-the art BaaS platforms available on the market, in this subsection, we introduce the leading BaaS platforms which are ready to use for BCoT applications. The key technical characteristics of each platform are described briefly in Table VI. The source code for BaaS examples and templates are also available on the code sharing platform Github. In fact, many research projects have employed such BaaS platforms to develop their BCoT applications. For example, the Amazon Blockchain service [188] is adopted to build an IoT healthcare system [105]. In this project, the Ethereum blockchain platform hosted on Amazon cloud helps to implement a health data sharing framework on mobile clouds with high security and privacy. Moreover, IBM cloud [187] also introduces a well-developed BaaS platform for IoT users. The platform has been showcased in a vehicular network [206]. In this project, the IBM IoT platform is integrated with IBM BaaS services to manage vehicle sensor data (vehicle-to-vehicle messages and vehicle monitoring data) and ensure security during data sharing within the vehicular network. Meanwhile, the BaaS platform of Oracle cloud [189] has proven its great potentials through a wide range of BCoT projects, such as banking, healthcare data management, and payment industry [207]. Recently, the Hewlett Packard cloud provider [190] collaborates with the automotive manufacturing giant Continental to launch a blockchain-based platform for car manufacturers to share and sell vehicle data [208]. This project allows customers, including vehicle drivers, car manufacturers and service providers can share securely vehicle data in untrusted vehicular networks, making mobility safer, greener, and more accessible. Although the development of BaaS platforms is still in progress, the success of such initial projects on BaaS platforms is expected to open up new opportunities for future BCoT deployments as well as disrupt global industries.

3) Blockchain IoT projects: Blockchain has been integrated widely in IoT projects to solve critical issues in terms of security, privacy and system performance as well as enable new IoT services in industries. Table VII summarizes information of the most popular blockchain IoT projects in various IoT scenarios such as energy, logistics, supply chain, and healthcare. Such blockchain IoT projects have also collaborated with cloud platforms such as Google, Microsoft Azure to deliver BCoT services for IoT users. We will review some of projects with deployment examples in the following.

IOTA [196] is a blockchain IoT platform established in Germany for transaction services in IoT. Many research projects have employed this platform for IoT applications, such as sensor systems [209], smart utility meter systems and smart car transaction [210], and IoT data management [211]. For example, the IOTA protocol is used in [210] to facilitate machine-to-machine (M2M) transactions of data from field IoT sensors using blockchain, enabling to secure data exchange and promote data monetization economy in sensor

TABLE V: Decentralized storage platforms based on cloud blockchain.

Platforms	Key features	Cloud support	Latest version	Last update	Ready to use?	Open source?
IPFS	Data file is hashed cryptographically for immutability.	Yes	v0.4.21	May 2019	Yes	Yes [176]
Storj	End-to-end encryption security is provided.	Yes	v04	Apr. 2019	Yes	Yes [177]
Filecoin	End-to-end encryption security is provided. Users can stored files with preferences based on cost budgets, redundancy, and file retrieval speeds	Yes	v 0.2.2	May 2019	Yes	Yes [178]
Sia	Stored files are encrypted. Storage is supper cheap with $2/ terabyte.	Yes	v1.3.3	Aug. 2018	Yes	Yes [179]
Swarm	Users can use local HTTP proxy API to interact with Swarm. Ethereum support is provided.	-	v 0.4.3	Jun 2019	Yes	Yes [180]
Maidsafe	Data file is uploaded to a safe network and is fully encrypted for privacy.	-	v4.18.2	2018	Yes	Yes [181]
BigchainDB	It combines the key benefits of distributed databases and traditional blockchains.	Yes	v2.0	2018	Yes	Yes [182]
Datum	Users can offload data to decentralized nodes via mobile application with smart contracts.	-	v0.1.33	2018	Yes	Yes [183]

networks.

Meanwhile, Modum [198] is a blockchain IoT start-up working on supply chain and logistics. It builds a safe, secure and reliable environment for supply chain automation and analytic services. A recent use-case of Modum is in the pharma supply-chain project [212], which provides security services (i.e. fraud detection, document verification and data tracking based on smart contracts) for shipment of medical goods between pharmaceutical distributors and pharmaceutical wholesalers. Furthermore, Power Ledger [202] is an Australian blockchain star-tup working on energy industries. It focuses on energy-related issues, including storage and distribution of power, energy business and smart energy. The project has been funded a $8 million government smart cities grant to trial a blockchain-powered distributed energy and water system in Fremantle [213] with the collaboration of Curtin University, Murdoch University, CSIRO/Data61, and CISCO organizations. Helium [205] is another ambitious blockchain IoT platform which is a fee-free peer-to-peer network for IoT devices. It also collaborates with cloud platforms such as Google and Microsoft to implement cloud blockchain projects. Very recently, Helium raises successfully $15 million for large-scale deployments of hotspot networks [214] in various IoT domains from pet collars and ride-share scooters to sensors that monitor air and water quality. Other projects such as IoT Chain [197], Waltonchain [204], OriginTrail [215], IoTex [216] also show potentials in blockchain IoT scenarios. They also mention benefits of blockchain in their involved projects as well as opportunities to expand their platforms by integrating with other advanced technologies, such as cloud computing, in the near future.

VI. Research challenges and future directions

From the extensive review on BCoT integrations, we identify possible research challenges and open issues in the field. Then, some future research directions are also pointed out to encourage more research efforts in this promising area.

A. Research challenges

In this subsection, we will highlight critical challenges brought by the BCoT integration. Several potential solutions for each challenge are also provided.

1) Standardization: Since its inception, the blockchain technology has revolutionized industries by offering new network models with its decentralized and secure natures. The arrival of this emerging technology is potential to change the current shape of Cloud of Things markets and transform industrial network architectures with advanced BCoT paradigms. Although the convergence of blockchain and Cloud of Things can bring various benefits to IoT applications, the BCoT technology has developed without standards and is limited to a few service providers. Importantly, each service provider mainly designs and offers BCoT for specific applications rather than generic schemes which can be applicable to diverse use-case domains. The lack of system standard can restrict potential collaborations between services providers and make customers feel difficult in changing providers as each provider has their own rules [27]. Furthermore, non-standard heterogeneous communication protocol between different blockchain platforms and Cloud of Things systems is still a critical issue for the BCoT market. For example, three cloud blockchain projects considered in [27] including Golem, SONM and iExec have different visions in terms of service provision, system configuration, and customer targets. Such a lack of standard arises from three main reasons: different service definitions, different network management concepts and different operational hypothesis. Consequently, they are unable to meet a standard service level agreement, which is very important for their project developments in a long run.

Possible solutions: Different BCoT service providers should achieve a service agreement on the incorporation of blockchain and Cloud of Things. Technical details such as network settings, blockchain deployment, IoT device integration, and service payment schemes should be considered carefully. Federation of service providers can be necessary to standardise the BCoT technology. Many standardization efforts have been made with the participation of a number of organizations such as ISO, ISTIC Europe, IEEE [217] to build a general functional architecture for blockchain platforms. Moreover, international BCoT standards will have to be developed simultaneously among multiple service suppliers in cloud blockchain design, market creation and customer service support, which promises to facilitate current BCoT-related industries [218].

TABLE VI: BaaS platforms for BCoT applications.

BaaS Platforms	Descriptions	Blockchain	Launch Year	Source code
Microsoft Azure Blockchain	Microsoft Blockchain on Azure is a BaaS platform hosted on the Microsoft Azure cloud computing for creating and configuring consortium blockchain infrastructure quickly. It is now available in two tiers: Basic for cost-optimized services to test blockchain apps and Standard for running real BCoT applications.	Ethereum, Hyperledger Fabric or R3 Corda	2016	[186]
IBM Blockchain	IBM blockchain is an enterprise-ready blockchain application development platform. It enables businesses to develop, govern, and operate blockchain systems with seamless software and network updates on IBM cloud. Some biggest banking and commercial industries have used IBM blockchain.	Hyperledger Fabric	2017	[187]
Amazon Blockchain	Amazon blockchain service makes it easy to setup, deploy, and manage scalable blockchain networks. It can be useful in many IoT use cases, such as manufacturing, insurance, trading, retail, and banking systems.	Ethereum and Hyperledger Fabric	2018	[188]
Oracle Blockchain	BaaS on Oracle cloud provides an enterprise-grade distributed ledger platform that can assist businesses to increase trust and provide agility in transactions across their business networks. Oracle BaaS can seamlessly connects with a number of popular Oracle solutions such as Oracle Supply Chain Management (SCM) Cloud and Oracle Enterprise Resource Planning (ERP) Cloud.	Hyperledger Fabric	2018	[189]
Hewlett-Packard (HP)	Blockchain HP launched its BaaS called HPE Mission Critical Blockchain, which enables customers to execute distributed-ledger workloads in industrial environments with high security. It also guarantees massive scalability of HP-based blockchain projects to support business.	Ethereum	2017	[190]
Alibaba Blockchain	Alibaba BaaS is an enterprise-level PaaS (Platform as a Service) which is built on Alibaba Cloud Container Service for Kubernetes clusters. It brings benefits such as high security, ease-of-use, high stability, openness and efficient sharing services for blockchain-based applications.	Ethereum and Hyperledger Fabric	2017	[191]
Baidu Blockchain	Baidu BaaS is a commercialized platform, to simplify Dapp development. It provides developers with services such as multi-chain and middle-tier frameworks, as well as smart contract and DApp templates on Baidu cloud computing. Its applications consists of IoT with BCoT, finance, and data sharing.	Ethereum, Hyperledger Fabric, and Baidu XuperChain	2018	[192]
Huawei Blockchain	Huawei BaaS is a cloud service that capitalizes on the advantages of Huawei clouds container and security technologies. It offers key advantages such as open, easy-to-use, flexible and efficient features as well as robust security and privacy protections.	Hyperledger	2018	[193]
Google Blockchain	Google BaaS is based on Ethereum platform with important features such as API integration, configurable consensus algorithms, and the ability to use a traditional SQL databases to query and report on blockchain data.	Ethereum	2018	[194]
SAP	SAP BaaS provides an easiest and lowest-risk gateway to experimenting with distributed ledger technology. It is hosted on SAP cloud platform, enabling to prototype, test, and build blockchain applications (both private and consortium) and smart contracts.	MultiChain and Hyperledger Fabric	2018	[195]

2) Security vulnerability: Although blockchain can bring security benefits to Cloud of Things thanks to its distributed nature, immutability, verifiability, and encryption, security issues in BCoT still remain due to the vulnerabilities of both Cloud of Things and blockchain systems. In Cloud of Things, there has been an increasing demand of outsourcing IoT data to clouds for storage and computation services due to the constrained resources of IoT devices. This dynamic incorporation has brought a series of new challenging security concerns such as identity and access control, authentication, system integrity [62]. Further, there are a number of critical security attacks to Cloud of Things, such as eavesdropping, malicious IoT attacks, unsecured communication channels, and degradation of connection quality. Cloud services for BCoT also suffer from serious security threats, from storage and computation attacks, virtual machine (VM) migration attacks to malware injection and denial-of-service (DOS) attacks [219].

On the other side, recent studies also have revealed inherent security weaknesses in blockchain operations which are mostly related to BCoT systems [220]. A serious security bottleneck is 51% attack which means that a group of miners controls more than 50% of the network's mining hash rate, or computing power, which prevents new transactions from gaining confirmations and halts payments between service providers and IoT users. Seriously, attackers can exploit this vulnerability to perform attacks, for example, they can modify the ordering of transactions, hamper normal mining operations or initiate double spending attack, all of which can degrade the blockchain network [220]. In addition, the security aspect of smart contract, which is regarded as core software on blockchain, is also very important since a small bug or attack can result in significant issues like privacy leakage or system logic modifications [221], [222]. Some of critical security vulnerabilities can include timestamp dependence, mishandled exceptions, reentrancy attacks on smart contracts in BCoT applications.

Possible solutions: Security problems in BCoT can be solved by security improvements in both Cloud of Things and blockchain systems. From the Cloud of Things point of view, security evaluations and appropriate solutions are vitally important. For example, the work in [223] proposed a trust assessment framework for cloud services named STRAF which takes into account security as a crucial feature to investigate trustworthiness of cloud computing to ensure security of cloud-based IoT applications. Furthermore, a cloud IoT architecture was also presented in [224] in which the

TABLE VII: Blockchain IoT projects.

Project Names	Application domain	Description	Launched year	Notable Partnerships	Project updates	Ref.
IOTA	Automotive, trade and supply chain industries	IOTA is a transactional settlement and data transfer layer for IoTs. It is based on a new distributed ledger, the Tangle, which overcomes the inefficiencies of current Blockchain designs and introduces a new method of achieving consensus in the P2P network. This projects also aims to enable secure trading and sales transactions for IoT applications.	2015	Microsoft, Volkswagen, Bosch, Fujitsu	April 8, 2019	[196]
IoT Chain	Vehicle, vaccine tracing and privacy apps	IoT Chain aims to make IoT a safer space for all users. As hosted on a lite operating system with blockchain, IoT Chain enables IoT data to be stored and layered in a decentralized manner. It also provide robust protection with the combined strength of the millions of IoT nodes within the network.	2017	Schonell, GVE, GMTech, Adzar Energy	April 20, 2019	[197]
Modum	Supply chain	Modum is a tech startup that aims to improve the currency supply chain process and offer analytic solutions. By combining IoT and blockchain, Modum can establish a supply chain network which combines IoT devices and smart contracts into one single device, ensuring to achieve user privacy and simplify value chain automation, and fulfilling regulatory and internal quality requirements.	2016	Comunications Systems Group, Swiss Commission for Technology	April 30, 2019	[198]
Factom	IoT, mortgage industry, healthcare records	Factom is a storage system for millions of real-time records which resides on a distributed and decentralized network on blockchain. The concept behind this project is to create a distinction between the Value Layer and the Data Layer, which enables document notarization.	2014	Digital Documents Equator, FPT Software	March 9, 2019	[199]
Ambrosus	Pharmacy, logistic and supply chain	Ambrosus is blockchain-powered IoT network for food and pharmaceutical enterprises, enabling secure and frictionless dialogue between sensors, distributed ledgers and databases to optimise supply chain visibility and quality assurance. The beauty behind Ambrosus is that it has use cases with any industry that relies on logistics and supply chain.	2017	Nestle, Trek Therapeutics, BioFirm AG, Crypto Valley Association, Cantone Group	April 29, 2019	[200]
VeChain	Supply chain	The VeChain project focuses on supply chain applications. It uses smart contracts to track company inventory and product during the supply chain process. RFID labels are placed on shipments, which then reveal the history of a product in its entirety. VeChain users can view this history any time they want as the shipment goes through the process.	2015	China Unicom, Bright Food, LogSafer, BYD, BIOS Middle East	Feb 13, 2019	[201]
Power Ledger	Renewable energy and environmental commodities trading	Power Ledger is a distributed, interoperable energy trading platform that supports an extensive suite of energy-focused applications. Power Ledger can create a market that allows energy to be exchanged securely between customers along with a shared ownership methodology based on blockchain.	2016	CSIRO, CISCO, Power Ledger, Australian Energy Market Operator (AEMO)	Jan 22, 2019	[202]
GridPlus	Retail energy industry	This project leverages the Ethereum blockchain to give consumers direct access to wholesale energy markets, responding intelligently to changes in energy prices. GridPlus products form a new, fully integrated infrastructure stack for mainstream use of digital assets and cryptocurrencies in energy networks.	2017	TepCo	March 15, 2019	[203]
Waltonchain	Supply chain	WaltonChain is a genuine, trustworthy and traceable business ecosystem with secure data sharing and absolute information transparency. It is built through a combination of the RFID and blockchain technologies. This method of inventory tracking is helpful in logistics, product kiosks, and library systems.	2016	Mitoq, Huodull, Kaltendin, Freyrchain, Fashionchain, MoneyNet	April 25, 2019	[204]
Helium	Ubiquitous internet of things	The Helium project simplifies interconnection among IoT devices and machines through a decentralized blockchain to incentivize businesses and communities. It is also integrated with available cloud platforms such as Google for BCoT applications.	2013	SalesForce, Google Cloud, Microsoft, Mouser, SparkFun	April 10, 2019	[205]

trust evaluation mechanism guarantees high security for IoT and enhance system trustworthiness. In the perspective of blockchain, there are also some security enhancements. For instance, a mining pool system called SmartPool [225] was proposed to improve transaction verification in blockchain mining to mitigate security bottlenecks, such as 51% vulnerability, ensuring that the ledger cannot be hacked by increasingly sophisticated attackers. Particularly, recent works [226], [227] introduced efficient security analysis tools to investigate and prevent threat potentials in order to ensure trustful smart contract execution on blockchain. Such research efforts make contributions to addressing security issues in BCoT environments and improving the overall performance of the system.

3) Privacy leakage: The privacy of IoT data in BCoT can be compromised accidentally and hence the disclosure of data is respectively beneficial for the attacker and harmful to the users. In current BCoT systems, data can be stored off-chain in cloud storage to reduce burden on blockhain. However, this storage architecture can arise new privacy concerns. Specifically, an autonomous entity can act as a network member to honestly perform the cloud data processing, but meanwhile obtains personal information without consent of users, which leads to serious information leakage issues. External attacks

can also gain malicious access to retrieve cloud data, or even alter and modify illegally outsourced IoT records on cloud. Besides, privacy leakage on blockchain transaction is another significant problem. Although blockchain uses encryption and digital signature to preserve transactions, recent measure results [228] show that a certain amount of transaction is leaked during blockchain operations and data protection of blockchain is not very robust in practice. Furthermore, criminals can leverage smart contracts for illegal purposes, facilitating the leakage of confidential information, theft of cryptographic keys. Importantly, privacy of BCoT users can not be ensured once they join the network. Indeed, by participating in the blockchain network, all information of users such as address of sender and receiver, amount values is publicly available on the network due to the transparency of blockchain. Consequently, curious users or attacks can analyse such information and keep track of activities of participants, which can lead to leakage of information secrets such as personal data.

Possible solutions: Innovative approaches have been considered to enhance privacy for BCoT systems such as encryption methods, trusted cloud computing, efficient user identification, access control, and intention hiding solutions [229]. Recently, an access control architecture was proposed in [230] to improve privacy of IoT data in cloud computing with better data reliability levels inherited by a consensus mechanism. From the blockchain view, anonymity plays a crucial role in ensuring robust privacy for BCoT users. In this regard, user information on blockchain can be hidden efficiently and attackers cannot guess identity of transactions and thus preserve private user information. For example, a recent work in [231] proposes a new solution with the ability to provide anonymity and unlinkability of senders, the privacy of transaction on the blockchain platform. Additionally, the authors in [232] present an anonymous reporting scheme which can ensure the reliability of anonymous reporting information without revealing the identities of IoT users, then preserving the privacy of blockchain systems.

4) Intelligence: Currently, BCoT systems are mainly used for data storage, data sharing and security services. However, there has been a lack of research attention in integrating intelligent services in BCoT applications. In fact, modern industries have increasing demands in intelligent services such as smart data analytics, smart decision making systems or automatic management tools to facilitate user service delivery. For example, a smart clinical support system based on cloud computing in healthcare can make diagnosis and treatment much easier. Further, an intelligent traffic analytic tool in cloud-based vehicular networks can help vehicle drivers to adjust their route for reducing possibilities of traffic congestion. All such intelligent services will be promising in BCoT-enabled applications to satisfy quality of user experience and enhance system efficiency. Therefore, we consider intelligence in BCoT as an important open issue where research efforts are strongly necessary.

Possible solutions: The adoption of expert systems and intelligent tools available on cloud computing may be a good solution to provide intelligence in BCoT-related applications. For example, in BCoT-based smart healthcare, machine learning for smart health assessment systems is useful to support doctors in medical processes [233], [234]. Meanwhile, in smart cities, big data analytic software available on cloud is very helpful to solve data-related issues such as data collection, processing and visualization for smart services from city environment, citizens and various departments and agencies in the city scale [235]. Specially, a recent research effort [236] was put on the integration of machine learning and blockchain to enable decision making services in a fashion intelligence of the system is improved while security and reliability are guaranteed.

5) Resource management: In BCoT applications, to achieve sustainable profit advantage, cost reduction, and flexibility in cloud service provision, resource management in cloud blockchain is vitally important and needs more research efforts. In fact, resource management in cloud blockchain networks requires adaptive and robust designs to solve series of technical problems, from resource allocation, bandwidth reservation to task allocation and workload allocation. A set of issues, challenges, and future research directions on resource management in cloud-based networks is discussed in [237], for example, the optimization of cloud resource allocation to computation demands and the adaption to dynamic service usage patterns. Such issues would become more complex when integrating cloud computing in blockchain where resource usage is divided to serve multiple purposes, including resource for user demands and resource for mining mechanisms to maintain blockchain. Therefore, there is an urgent need to seek innovative solutions to overcome challenges in terms of resource management in integrated BCoT networks.

Possible solutions: Some intelligent approaches have been proposed recently to enhance efficiency of resource management in BCoT. For example, the authors in [142] presented a framework for energy-aware resource management in cloud datacentres with blockchain. Machine learning is embedded to smart contracts to optimize energy consumption according to user requests. This solution also has the potentials to achieve significant cost savings in respect with request scheduling and request migration on cloud blockchain. Meanwhile, the issue of resource management for mining blockchain in BCoT is considered in [238] in which resource for computation in the blockchain consensus process is optimized to achieve minimum prices of service usage. It also demonstrates that cloud providers can gain benefits from the optimal resource management with better profits in the proposed public cloud blockchain networks.

In summary, research towards improving the performance of cloud blockchain platforms and the overall BCoT systems is still in early stages. Although several contributions have been provided, we consider challenges during the development of BCoT technology as significant open problems which requires more new ideas, proposals and disruptive innovations. A lot of research needs to be done to fill this gap and make BCoT-based applications competitive in real markets.

B. Future directions

As BCoT has attracted widespread attention of both academics and industries, its developments are likely to be

affected by other technologies. The convergence of BCoT and these technologies can open up a wide range of opportunities to future services and applications. In this section, we will provide insights of such technologies and present the future research directions of integrating BCoT in such technologies to empower both worlds.

1) Machine learning: The revolution of machine learning technology transforms current IoT services by enabling its ability to learn from data and provide data driven insights, decision support, and predictions. These advantages of machine learning would transform the way data analytics are performed to assist intelligent services in IoT. Recent years, there is a growing trend of integrating machine learning in BCoT scenarios. Some works in [235], [236] demonstrate the efficiency of machine learning tools in improving intelligence of BCoT applications. Specially, deep reinforcement learning (DRL) [239] has recently emerged as one of the most attractive machine learning techniques to solve many critical issues in BCoT networks. Indeed, it is proven that DRL can be useful to address effectively issues in terms of blockchain mining processes by offering offloading and resource allocations algorithms [240]. Furthermore, the integration of DRL can overcome security challenges brought by the dynamic data exchanges among blockchain users and information flow over untrusted mobile environments in cloud-blockchain systems. Our recent works verify that DRL-based offloading for consensus mechanisms in mobile blockchain networks can achieve privacy preservation for blockchain users [241] and security improvements for BCoT systems [242]. Obviously, the adoption of machine learning provides more perspectives to evaluate, analyse and deal with existing issues in BCoT scenarios, enabling to boost QoS, security and performance of the whole network.

2) Edge computing: As an extension of cloud computing, edge computing has emerged as the promising technology to empower BCoT systems [28]. Edge computing may have other names such as fog computing, mobile cloud or cloudlet. Similar to the cloud paradigm, edge computing can offer series of computing services with capabilities of task processing, data storage, heterogeneity support and QoS improvements. In fact, edge servers are less powerful than remote clouds, but they are located at the edge of the network, with a close proximity to IoT devices, which enables highly efficient IoT data computation with much lower transmission delay, compared with the remote cloud. As a result, edge computing can provide instant computing applications to IoT users with low latency and fast service response, which would be particularly useful in the next generation services (i.e. in 5G and beyond). The distributed structure of edge computing also potentially brings numerous benefits, from ubiquitous computing services, scalability improvement to complexity reduction of network management to cope with the explosion of IoT devices and rapid growth of IoT service demands [28].

Nowadays, edge computing has been leveraged to implementation of BCoT systems. For example, task offloading services can rely on edge computing associated with cloud to execute BCoT tasks so that network latency and system energy usage can be minimized [242]. It also provides insights into how to efficiently reduce burden on constrained-resource IoT devices and ensure robustness of the BCoT system. In [243], edge computing is adopted to enable resource allocation for blockchain mining. In this context, the edge computing service providers work as resource sellers, while miners (i.e. mobile devices) act as buyers. In addition, another research in [244] shows that edge computing can support content catching strategies in the context of mobile blockchain where IoT devices can also decide to offload their tasks to the edge server or nearby devices for task execution.

3) Unmanned Aerial Vehicles (UAVs): The rapid growth of drones or Unmanned Aerial Vehicles (UAVs) [245] is creating numerous new business opportunities for service providers. UAVs can be regarded as flying IoT devices and have been employed widely in various areas, ranging from military, security, healthcare, and surveillance to vehicle monitoring applications [246]. In the era of modern 5G communication networks, due to the rapidly growing IoT traffic, it is very challenging for static base stations (i.e. access point, router) to support data demands of billions of IoT devices in large scale BCoT scenarios. Therefore, the adoption of UAV in IoT networks can be a future direction. Indeed, UAV can act as a flying base station to support unprecedented IoT services, i.e. dynamic data offloading, data sharing or service collaboration, due to its mobility and flexibility [247]. The UAV technology is an ideal choice to connect and coordinate numerous IoT users and service providers. Recent years have witnessed research efforts in the use of UAV to empower BCoT applications. For instance, the work in [248] integrates UAVs with blockchain to enable efficient content dissemination and improve security against denial of service attacks in vehicle ad hoc networks. In [249], the combination of UAV and blockchain is considered, enabling flexible and secure communication and improving business efficiency. Meanwhile, the authors in [250] adopt UAVs as on-demand nodes for efficient data caching with edge computing. Ultra-reliability of the user network is ensured by the blockchain-based peer-to-peer network. Such pioneering works are expected to encourage new research ideas and innovations dedicated to the UAV-blockchain integration paradigms, aiming to promote the development of BCoT technology.

4) Big data: In the age of data explosion, big data becomes a hot research topic coupled with BCoT. A large amount of multimedia data generated from ubiquitous IoT devices can be exploited to enable data-related applications, for example, data analytics, data extraction using machine learning [236]. Cloud computing services can offer high storage capabilities to cope with the expansion of quantity and diversity of digital IoT data. However, big data technologies can face various challenges, ranging from data privacy leakage, access control to security vulnerabilities due to highly sophisticated attacks and data thefts. In such contexts, blockchain in BCoT appears as the ideal candidate to solve big data-related issues [251]. Indeed, the decentralized management associated with authentication and reliability of blockchain can provide high security guarantees to big data resources. Specially, blockchain can offer transparency and trustworthiness for sharing of big data among service providers and data owners. By eliminating

fear of security bottlenecks, BCoT can enable universal data exchange which empowers large-scale BCoT deployments. Recently, some big data models enabled by blockchain are proposed, such as data sharing with smart contracts [252] or data tracing solutions using blockchain transaction [253]. Such preliminary results show that blockchain can bring various advantages in terms of security and performance to big data applications, which will be promising to the development of both worlds.

VII. Conclusion

In this paper, we have presented an extensive and up-to-date review of the integration of two disruptive technologies: blockchain and Cloud of Things. We name the synthesis of such corporation as BCoT which is becoming increasingly important in industrial applications due to its high security, privacy, service support and system performance enhancement. This survey is motivated by the lack of a comprehensive literature review on the development of BCoT systems. We have first provided a brief overview on the background knowledge and recent evolution of blockchain and Cloud of Things technologies. Motivations of the integration and opportunities arising from the BCoT adoption are also discussed. Then, we have provided the integrated architecture with three layers where the convergence of blockchain and cloud computing in IoT is analysed. In particular, we have presented a comprehensive survey on the use of BCoT models in various applied scenarios, ranging from smart healthcare, smart city, smart transportation to industry applications and cloud services. The vision of BCoT in the next generation 5G networks has also been explored. We have further surveyed available BCoT platforms and research projects that would be useful to application developers and researchers who are interested to gain insights into this emerging paradigm. From the extensive literature review on BCoT applications, we derive important technical challenges, and then analyse them to identify possible research directions. Finally, several future research directions are pointed out to enable the next generation of the BCoT technology.

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