Decentralized Smart IoT

Subjects: Computer Science, Information Systems

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Decentralized smart Internet of Things (IoT) refers to future IoT powered by blockchain-enabled edge intelligence. This new form of IoT is motivated by the recent advancement of distributed ledger technology (DLT), multi-access edge computing (MEC) and artificial intelligence (AI). The idea is to empower all kinds of IoT devices to observe, identify, and understand the world not by the help of humans but by cooperation and consensus among edge devices, in a secure and verifiable manner. Decentralized smart IoT will provide trust and intelligence to satisfy the sophisticated needs of industries and society.

Internet of Things blockchain multi-access edge computing machine learning

1. Introduction

Internet of Things (IoT) emerged initially in 1999 in supply chain industries in association with radio-frequency identification (RFID) [1]. The idea was to empower computers to observe, identify, and understand the world without the help of human beings. However, many IoT devices are designed to be battery operated and have a compact physical size; thus, they have very limited energy and computation resources. Such resource-constrained IoT devices are not well-equipped to perform complex processing, such as supporting artificial intelligence (AI) [2]. Although federated learning (FL) can be implemented by a group of IoT devices [3], such computational workload is still too heavy for IoT devices.

To overcome this bottleneck, transmitting computational tasks to nearby servers is an attractive solution. Different from traditional cloud computing, such strategy as multi-access edge computing (MEC) delivers computation resources to the edge of the radio access network (RAN). Therefore, computational tasks have no need to travel through the core network, allowing IoT data to be processed and results consumed locally with minimal delay. This mode of computing, while minimizing latency and use of core network communication resources, has its own challenges. For example, security issues and incentives should be taken into considerations. To be specific, the transmitted data may contain private data about personal identity and financial account information. This raises the risk of privacy leakage and malicious attacks. Moreover, nearby servers or computing nodes may need incentives to process tasks for IoT devices. Furthermore, edge servers have limited computation power compared with the cloud. The computing operations also cost storage and energy resources. Therefore, a computing resource trading [4] and data sharing [5] framework or platform is needed to motivate edge servers.

As a distributed ledger technology (DLT), blockchain has emerged as a potential solution for the above issues, due to its nature of data transparency, distributed operation, and reliability. Therefore, it is essential to apply blockchain to edge intelligence in support of IoT applications. Blockchain refers to a set of records that are sequentially chained together using cryptography. Generally speaking, a blockchain uses “consensus” to add new data records (not replace them). However, traditional databases use “permission” to manage data. It has centralized administration and maintenance. Therefore, blockchain has become a powerful decentralized model to establish trust among trustless entities, in a verifiable manner.

2. MEC for Decentralized IoT

To realize decentralized smart IoT, MEC and blockchain are integrated together. In general, the integration between blockchain and MEC is mutually beneficial [6]. On one hand, blockchain introduces security, privacy, and trust to MEC [7][8]. Efficient control and incentive of cooperation among edge devices and servers are securely enabled by blockchain. On the other hand, MEC improves the scalability of blockchain in a distributed and efficient manner by delivering computing and cache resources to the blockchain-enabled IoT systems. For example, blockchain mining requires a high computational capability in the PoW process, which imposes great challenges for IoT devices. The reason why IoT devices should actively mine is that a global consensus is required for transaction validation. Different from a distributed IoT system, a blockchain-enabled IoT system decentralize the authority to each IoT device. In other words, there is no single third party that could help IoT devices make a global decision. Therefore, the PoW mechanism needs to be in place to confirm and secure the integrity and validity of transactions. Fortunately, MEC can be introduced as a solution to this issue. By offloading computational tasks to an MEC server, resource-constrained IoT devices can use PoW to reach consensus for decentralized applications.

Nguyen et al. [9] discussed the privacy leakage issue in blockchain-MEC integration. In this article, mobile users act as miners in the blockchain system. Data processing tasks and mining tasks are offloaded from users to nearby MEC servers. The privacy level of this process is modeled and formulated. Furthermore, blockchain was introduced as a strong security mechanism for MEC systems in vehicular networks [10]. In addition, Reference [11] introduced a blockchain-based trust mechanism for MEC systems. By establishing a reputation system for the edge nodes, the miner in the blockchain network was, thus, selected in a trusted manner.

Additionally, blockchain-enabled payment systems for the video streaming industry were developed with an incentive mechanism for MEC servers [12]. Furthermore, the flexibility and scalability of block size could be significantly improved by MEC. However, not every edge device could have enough cryptocurrency to buy the offloading service. Therefore, Zhang et al. [13] proposed a loan strategy for this purpose. Although the mining task could be executed on MEC servers, competition exists among IoT devices. The reason is that the resources of edge servers are still limited compared to relatively numerous IoT devices. To deal with this issue, Zhao et al. [14] solved the computation resources allocation problem in the MEC-assisted public blockchain network. Moreover, this strategy could protect the blockchain system from 51% attack [15] because the attacker with the majority stake in this system would try to preserve and secure this kind of cryptocurrency, but not to destroy it.

3. Decentralized AI for IoT

Traditional AI solutions, including deep learning and reinforcement learning, require the centralized governance of data. A single learner should gather data and computing resources for learning machines and agents before the training exercise. This centralized architecture leads to several issues, such as single points of failure and personal data leakage [16]. As mentioned above, blockchain is a decentralized and distributed record system. This characteristic is very suitable for deploying AI solutions in distributed IoT systems. Moreover, collaboration and trusted data sharing among learning machines could be realized by blockchain technology. In this review, we focus on introducing smart contract-based AI, especially the federated AI solution.

In a nutshell, smart contract [17] is a powerful tool to enable distributed and decentralized ML for IoT systems. As illustrated in Figure 1, this kind of predefined and self-verified scripts, including learning algorithms and models, can be deployed at each distributed learning device in a decentralized manner. Furthermore, only learning parameters are shared and verified by blockchain transactions, while sensitive IoT data are not accessible to any third parties. This guarantees the secure sharing of the learning experience and gives the self-governance of data to each entity, which is the basic idea of blockchain-based FL. Thus, blockchain and smart contact together enable a global platform for collaborating ML in a distributed and decentralized manner.

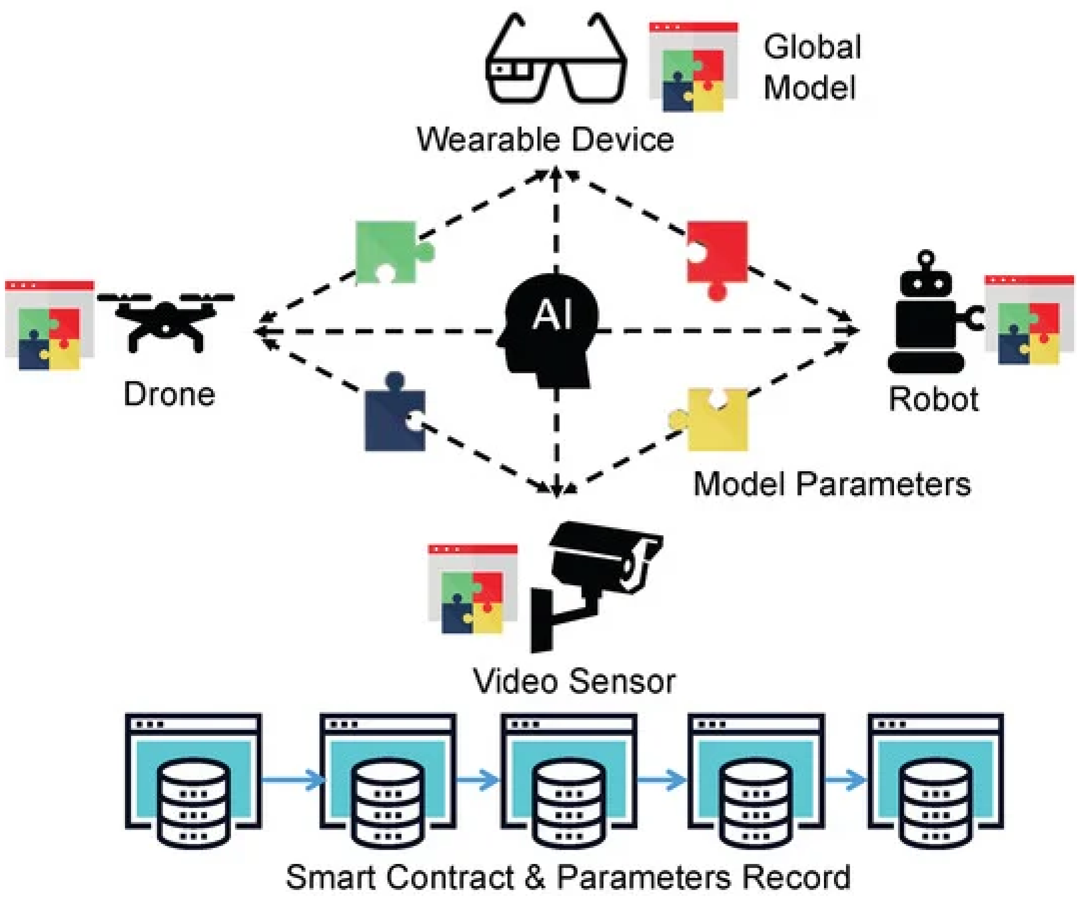

Figure 1. Blockchain-based artificial intelligence (AI) for the Internet of Things (IoT).

Blockchain was introduced to manage the reputation of learning devices [18][19][20][21][22]. To be specific, Kang et al. [19] proposed effective incentive mechanisms for reliable FL. Consortium blockchain was further introduced by them for reputation management. Moreover, blockchain-enabled reward systems were considered in References [4][23][24][25][26][27]. Furthermore, the blockchain-enabled data integrity and sources validation could be realized by deep learning with convolutional neural networks [28], giving the trustworthiness of training data quality. Moreover, Ma et al. [29] investigated data noise and the decentralized solution for data cleaning with edge intelligence.

Lu et al. [16] gave a secure data sharing architecture for decentralized and secure learning strategies to solve the privacy issue in ML. Moreover, the computing work in the blockchain consensus process was used for FL. Furthermore, Qu et al. [23] introduced poisoning attacks in decentralized ML. Likewise, Kang et al. [19] and Ramanan and Nakayama [30] proposed reliable FL strategies by removing the centralized model aggregator in ML. Plus, Yin et al. [31] investigated a blockchain-based federated deep learning in the IoT domain. This strategy was motivated by multiparty secure computation, which was also investigated in Reference [32]. Besides, Liu et al. [33] used smart contracts in the self-defense of FL. Membership inference and poisoning attacks were, thus, prevented in this way.

4. Decentralized IoT Communications

There are multiple research directions in decentralized IoT communications. We classify and list them as follows:

- *5G and beyond*: Although the 5G network improves services for IoT communications [34], it may not be capable of enabling new IoT applications, including telemedicine, haptic communication, bio-IoT, etc. Khan et al. [35] provided some future directions for IoT communication in 6G systems. In terms of blockchain-enabled edge intelligence, there are multiple research directions related to IoT communications. For 5G and beyond, Lu et al. [36] discussed blockchain and FL particularly. Potential application scenarios were listed in this paper, including intelligent transportation, mobile networks, network data analysis, etc. Moreover, IoT automation could be realized by 6G-enabled MEC. Sekaran et al. [37] pointed out research challenges in terms of IoT-enabled 6G devices. Furthermore, Nguyen et al. [38] discussed the function of blockchain in 5G and beyond networks in-depth.

- *Decentralized D2D*: For blockchain-enabled edge intelligence, device-to-device (D2D) communication is a feasible solution for data sharing and collaboration. Furthermore, blockchain gives the feature of decentralization to D2D. Particularly, Seng et al. [39] investigated ultra-dense wireless networks (UDNs). A decentralized computation offloading platform was proposed to coordinate tasks among devices and edge servers. Furthermore, Zhang et al. [24] studied cache sharing for data delivery. To assist MEC based offloading for inter-domain traffic, they proposed a blockchain-enabled market to motivate both D2D and MEC nodes. Plus, a partial Practical Byzantine Fault Tolerance protocol was proposed to minimize latency and guarantee the confidence level of the D2D sharing.

- *Edge Computing*: The tradeoff between limited resources and required latency is a major challenge for edge computing. To deal with this issue, Wu et al. [40] considered the collaboration of edge and cloud. They proposed an energy-efficient IoT task offloading algorithm for blockchain-enabled edge computing. Additionally, Xu et al.

[41] studied crowd-intelligence. An ecosystem was designed for trustless and hybrid human-machine crowd-intelligence. Zhang et al. [42] further investigated edge service migration. A blockchain-based secure edge service migration, namely Falcon, was proposed to extend the service scalability and flexibility. Furthermore, Chuang et al. [43] presented a trust-aware IoT data economic system (TIDES). The trading process in MEC systems was entirely based on the smart contract. Furthermore, Feng et al. [44] optimized the allocation of limited radio and computational resources. The scheduling of block producers was considered in this resource allocation. Furthermore, fast transaction writing and maximum mining revenue should be considered separately according to different IoT device requirements. A blockchain-based offloading strategy was given for the above scenarios in MEC systems [45].

- *Edge Caching*: Content caching is a popular solution to the ever-increasing IoT data traffic. Liu et al. [46] gave the offloading mode selection and caching strategy for wireless blockchain networks. A novel MEC-enabled wireless blockchain framework was further given for computation offloading and content caching [47]. Besides, ultra-reliable communication is a popular trend. Sharma et al. [48] used neural-blockchain for ultra-reliable caching in drone networks. Additionally, Cui et al. [49] implemented FL for content caching in edge computing. A novel compressed algorithm of the FL approach, namely CREAT, was proposed for this edge caching case.

- *Distributed Network Function Virtualization*: As a fundamental technology of software-defined industrial IoT [50] [51], network function virtualization (NFV) has emerged in blockchain-enabled edge intelligence recently. Distributed NFV offers a flexible way for large scale IoT networks management. Fu et al. [52] proposed a blockchain-based framework to reach consensus across different management and orchestration systems. Furthermore, a novel distributed software-defined network (SDN) architecture was proposed to control fog nodes at the network edge [53].

Table 1 summarizes the literature on IoT communications and their related research directions.

Table 1. Research directions and related literature on IoT communications.

Directions	Ref.	Contributions
5G and Beyond	[54]	Provide proof-of-concept for blockchain applications in 5G and beyond networks.
	[38]	Investigate the potential of blockchain in 5G and beyond network for IoT.
	[37]	Suggest guidelines toward blockchain enabled IoT with 6G communication.
	[36]	Propose blockchain-enabled learning framework for 5G beyond scenarios.
Decentralized D2D	[39]	Propose decentralized platform design for D2D computation coordination in UDNs.
	[24]	Optimize the decentralized D2D sharing and design the consensus for transactions execution.
Edge Computing	[40]	Propose an energy-efficient IoT task offloading algorithm for blockchain-enabled edge computing.

Directions	Ref.	Contributions
	[41]	Design a trustless hybrid human-machine ecosystem for industrial IoT based on crowd-intelligence.
	[42]	Propose a novel service migration framework for flexible edge service.
	[43]	Propose a trust-aware data trading system for MEC.
	[44]	Design the joint resources allocation for blockchain-enabled MEC systems.
	[45]	Propose a blockchain-based offloading strategy in MEC scenarios
Edge Caching	[46]	Propose caching strategy for wireless blockchain networks.
	[47]	Design an MEC-enabled wireless blockchain framework.
	[48]	Propose an ultra-reliable drone-caching approach enabled by neural-blockchain.
	[49]	Propose edge caching solutions based on FL.
Distributed NFV	[52]	Propose a distributed NFV framework for management and orchestration based on the MEC-enabled blockchain.
	[53]	Propose a novel distributed network architecture for fog nodes based on SDN.

5. Trends in Decentralized Smart IoT

In this part, we select and introduce some recent advances related to decentralized smart IoT. These topics are not fully investigated yet, but a few high-quality works have already been done. We aim at highlighting these new topics for researchers who wish to glimpse the latest research trends in this area. In addition, these advances further support that blockchain-enabled edge intelligence is an important enabler across different IoT industries.

- *Video Streaming*: Traditional video streaming requires centralized governance of data, which leads to centralized and low-profit video processing. Moreover, this centralized management and distribution of a large volume of video content require substantial data storage and communication bandwidth at a huge cost. In addition, video streams have to be converted into several versions to meet the different requirements of downloaders, by a process called video transcoding [55] that is a computation task with a heavy workload. By exploiting blockchain-enabled edge intelligence, transcoding tasks can be offloaded to MEC servers and user privacy is also secured. This approach was proposed by Liu et al. [56], and smart contracts were further implemented to enable self-organized video streaming. Lui et al. [12] further proposed an adaptive block size scheme in Reference [12], together with an autonomous content delivery market based on smart contracts. The authors further developed incentive mechanisms to facilitate collaboration among content providers, transcoders, and downloaders in Reference [57].

- *Tactile Internet*: Ultra-low delay communication is the main feature of the tactile Internet, which could be brought into reality With the help of 5G and beyond networks. This has motivated multiple research works and applications, such as haptic communications [58] and real-time telesurgery [59][60]. By bringing computing and caching resources close to end devices, MEC becomes the key to realize the above delay-sensitive application. A few papers have investigated the blockchain-enabled tactile Internet incorporating MEC. For example, Hassija et al. [61] proposed a blockchain-based mobile data offloading scheme to deal with the efficiency and scalability issues in tactile Internet. Furthermore, drone-based tactile Internet was studied in Reference [62]. A blockchain-based security framework was introduced to replace heavy security algorithms for resource-constrained drones.

- *Digital Twins*: Real-world physical components can be virtualized into the digital world. This real-time simulation is like a man in a mirror. All replicas of the same physical component are called digital twins (DTs) [63]. Furthermore, blockchain was investigated in this paper to ensure transparency, trust, and security across different industries. Moreover, blockchain-enabled low-latency FL was proposed for edge association in DTs wireless network [64]. The time cost and learning accuracy were balanced by exploring multi-agent reinforcement learning optimization. Furthermore, Lu et al. [65] explored empowering FL with permissioned blockchain to improve communication security and data privacy protection in DTs edge networks.

We further propose some emerging trends according to the timeline in Figure 2. The selected topics have occurred in the existing literature frequently. One can see that we slice the related topics according to the years of publications. In addition, more and more topics and related works emerge as time goes by. This means the decentralized smart IoT is evolving and becoming more popular.

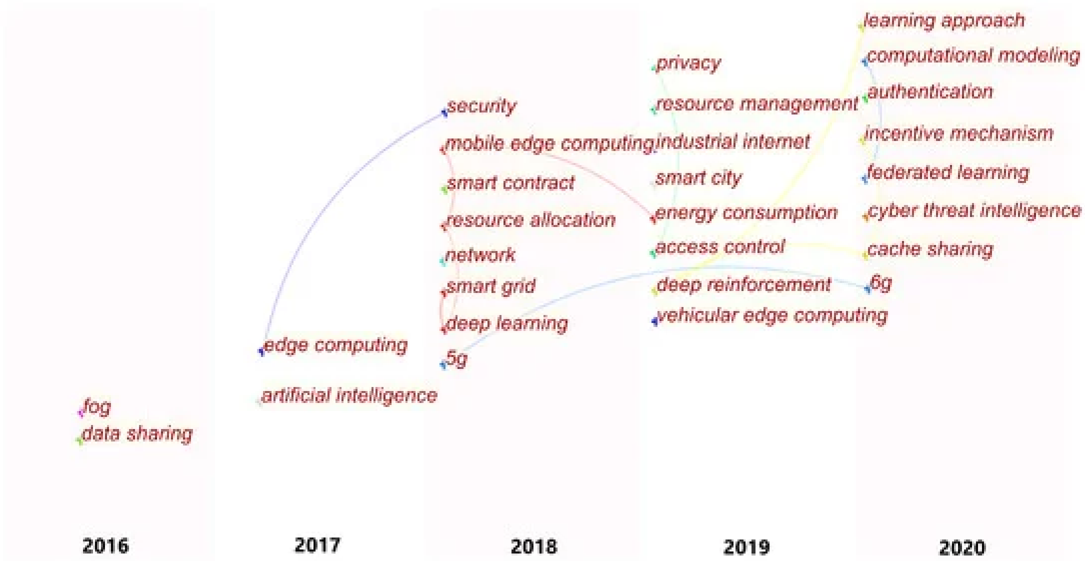

Figure 2. Emerging trends according to timeline.

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