Guest Editorial: Special Issue on Blockchain and Edge Computing Techniques for Emerging IoT Applications

WITH the emergence of 5G, wireless sensor networks, and related technologies, Internet of Things (IoT) has gained prominence as an emerging paradigm to meet the demands of flexible, agile, and ubiquitous accessibility of cyberspace from physical systems. However, the current centralized IoT architecture is heavily restricted by the problems of single points of failure, data privacy, security, and robustness. Recently, blockchains have been found attractive as potential solutions to some of these problems, due to their ability to maintain immutable open ledgers that are accessible to everyone but are tamper-proof. In addition, rapid development of edge computing has enabled a large range of new IoT applications. Edge computing pushes cloud services from the network core to the network edges in closer proximity to IoT devices. Thus, blockchain and edge computing are attractive technologies to meet new and existing challenges by enabling new IoT applications and services through secure, reliable, flexible, and powerful devices and systems while motivating new business models in the growing digital economies. They can provide attractive solutions, such as schemes for decentralized services, service virtualization, rapid resource optimization, and flexible and reliable management and maintenance.

In this special issue, we have received a large number of submissions, and after rounds of careful reviews and revisions, 31 high-quality papers have been selected for publication. The 31 accepted articles can be broadly categorized into four groups: the nine articles in the first group address how blockchain assist edge computing; the second group of six articles addresses the problem of blockchain for edge intelligence; the third group, with eight articles, studies the integration of blockchain and edge computing; and the eight articles in the fourth group discuss the novel blockchain-based applications.

A. How Blockchain Assist Edge Computing

The topics of the nine articles in this group can further be subdivided into the following three different aspects.

1) Essential Characteristics of Blockchain-Assisted Edge Computing: Feng *et al.*, in "Blockchain-based data management and edge-assisted trusted cloaking area construction for location privacy protection in vehicular networks," proposed a trusted cloaking area construction scheme to protect the location privacy of vehicles based on blockchain. In the article "Securing SDN-controlled IoT networks through edge blockchain," Hu *et al.* proposed a blockchain-aided software-defined network (SDN) using mobile-edge computing (MEC) and design the workflow of flow verification and verification of the proposed architecture to reduce the computational burden on the IoT systems. The article "Blockchain-based decentralized authentication modeling scheme in edge and IoT environment" by Zhaofeng *et al.* provides a more secure, reliable, and strong solution for fault tolerance based on the proposed blockchain-based decentralized authentication modeling scheme in edge and IoT environments.

2) Services of Blockchain Under Edge Computing: In the article "A blockchain-driven IIoT traffic classification service for edge computing," Qi *et al.* designed a lightweight Industry IoT (IIoT) traffic classification service by taking advantage of the hash and consensus mechanisms in blockchain to realize hash-table-based traffic classification across edge nodes. Gu *et al.*, in "Joint chain-based service provisioning and request scheduling for blockchain-powered edge computing," redefined the joint problem of service provisioning and request scheduling in ultra-dense edge clouds by proposing a chain-based service request model for emerging IoT applications. The article titled "Distributed charging-record management for electric vehicle networks via blockchain" by Qian *et al.* investigates blockchain-enabled charging-record management for electric vehicles. Moreover, storage-selection and server-node allocation for each blockchain is formulated as a joint optimization problem, with the objective of minimizing a systemwise cost for storing all the charging-records.

3) Specific Applications of Blockchain-Based Edge Computing: In the article "EEDTO: An energy-efficient dynamic task offloading algorithm for blockchain-enabled IoT-edge-cloud orchestrated computing" by Wu *et al.*, a blockchain-enabled IoT-Edge-Cloud computing architecture is proposed with the objective to minimize the energy consumption within a given delay constraint. An IoT-Edge-Cloud hybrid task offloading model is formulated, while a cost-driven scheduling strategy between communication and computation is designed for processing delay-sensitive applications efficiently. Yi *et al.*, in "Social interaction and information diffusion in social Internet of Things: Dynamics, cloud-edge, traceability," investigated the dynamic interplays between social interaction and information diffusion in social IoT. With the help of blockchain, a cloud–edge architecture is designed for traceability and security of information diffusion in social IoT. The article "Near-online tracking with co-occurrence constraints in blockchain-based edge computing" by Sheng *et al.* presents a novel blockchain-based near-online framework

Digital Object Identifier 10.1109/JIOT.2021.3050050

for cross-camera tracking in edge computing environments. Assisted by blockchain, tracking information is shared among edges with high confidence and low latency.

B. Blockchain for Edge Intelligence

The six articles in this group, which address various applications of blockchain for edge intelligence and explore the issues on robust routing, resource allocation, learning model updates, and communication efficiency, are summarized as follows.

1) Blockchain-Based Routing Design in Edge Computing: The article titled "Adaptive and robust routing with Lyapunov-based deep RL in MEC networks enabled by blockchains" by Zhuang *et al.* proposes a novel DRL-based adaptive routing method to tackle routing control problem in an environment with time-variant link delays. Lyapunov optimization is employed to reduce the upper bound of the Lyapunov drift, which can improve queuing stability in the networked systems. Specifically, they design a blockchain-based protocol using proof of elapsed time consensus mechanism to ensure a trustworthy network statistics exchange for the routing framework. Experimental results show that the proposed method can learn a routing policy and adapt to the changing environment.

2) Blockchain-Based Resource Allocation for Edge Computing: Aiming to tackle the security and privacy issues in IoT, the article "Blockchain-based edge computing resource allocation in IoT: A deep reinforcement learning approach" by He *et al.* proposes a general framework for blockchain-based edge computing-enabled IoT scenarios. A smart contract is designed within a private blockchain network that exploits the state-of-the-art machine learning algorithm, asynchronous advantage actor–critic (A3C), to allocate the edge computing resources. The article "When deep reinforcement learning meets federated learning: Intelligent multitimescale resource management for multiaccess edge computing in 5G ultradense network" by Yu *et al.* presents an intelligent ultra-dense edge computing (I-UDEC) framework in 5G ultra-dense network environments and a novel two-timescale deep reinforcement learning (2Ts-DRL) algorithm to achieve real-time and low overhead computation offloading decisions as well as resource allocation strategies. Especially, federated learning (FL) is used to protect the data privacy of edge devices during the training process. The article titled "Hybrid blockchain-based resource trading system for federated learning in edge computing" presents a hybrid blockchain-based resource trading system that considers the advantages of both public and consortium blockchains to achieve an automatic, autonomous, and auditable rational reverse auction mechanism among edge nodes. Specifically, the system leverages the payment channel technique to enable credible, fast, low cost, and high-frequency payment transactions between requesters and edge nodes.

3) Blockchain-Based Utilizations of Learning Model for Edge Networks: To explore the question of whether model updates from participants in blockchain-assisted FL can disclose properties of the private data the participants do not intend to share, the article titled "Exploiting unintended property leakage in blockchain-assisted federated learning for intelligent edge computing" by Shen *et al.* tries to attack current blockchain-assisted FL system by a novel way. More specifically, the method can learn the property leakage from model updates of participants and identify a set of participants with a certain property. The experimental results demonstrate that the proposed attack is effective and efficient in inferring various properties of training data. The article titled "Communication-efficient federated learning and permissioned blockchain for digital twin edge networks" by Lu *et al.* investigates how to integrate digital twins with edge networks, and proposes the digital twin edge networks (DITENs) to fill the gap between physical edge networks and digital systems. Specifically, to strengthen the communication security and data privacy protection in DITEN, the article puts forward a blockchain empowered FL scheme. Furthermore, to improve the efficiency of the integrated scheme, an asynchronous aggregation scheme and digital twin empowered reinforcement learning are used to schedule relaying users and allocate bandwidth resources. Theoretical analysis and numerical results confirm the effectiveness of the proposed scheme.

C. Integration of Blockchain and Edge Computing

The eight articles in the third group mainly discuss how blockchain may be integrated with various IoT networks.

1) Blockchain-Based Applications in IIoT Scenarios: The article by Miao *et al.* "Smart micro-GaS: A cognitive micro natural gas industrial ecosystem based on mixed blockchain and edge computing" proposes smart microgas, i.e., a cognitive micro natural gas industrial ecosystem based on mixed blockchain and edge computing. Wu *et al.*, in "Convergence of blockchain and edge computing for secure and scalable IIoT critical infrastructures in Industry 4.0," introduce the IIoT critical infrastructure in Industry 4.0 and briefly present the blockchain and edge computing paradigms. In addition, a survey on state-of-the-arts security and privacy, and scalability of IIoT critical infrastructures is provided. The article "Energy-efficient resource allocation for blockchain-enabled Industrial Internet of Things with deep reinforcement learning" by Yang *et al.* integrates MEC into blockchain-enabled IIoT systems to promote the computation capability of IIoT devices and improve the efficiency of consensus process.

2) Potential Blockchain-Based Applications for IoT Networks: Yang *et al.*, in "Distributed resource management for blockchain in fog-enabled IoT networks," present a distributed matching mechanism to maximize the social welfare of resource-restricted fog nodes while guaranteeing various mining requirements of fog nodes. The article by Liu *et al.*, titled "Blockchain-enabled secure data sharing scheme in mobile-edge computing: An asynchronous advantage actor–critic learning approach" proposes a secure data sharing scheme in blockchain-enabled MEC systems using an asynchronous learning approach. Numerical results demonstrate the superiority of the proposed secure data sharing scheme when compared with other popular benchmark algorithms in terms of average throughput, average energy consumption, and reward. "A data set accuracy weighted random forest algorithm for IoT fault detection based on edge computing and blockchain" by Zhang *et al.* presents a data set accuracy weighted random forest (DAWRF) fault detection algorithm based on edge

computing. The blockchain used in DAWRF can verify the accuracy of the data and ensure that they cannot be tampered with. Li *et al.*, in "NOMA-enabled cooperative computation offloading for blockchain-empowered Internet of Things: A learning approach," propose a multiagent deep reinforcement learning framework to achieve long-term performance for cooperative computation offloading, in which a scatter network is adopted to improve its stability, and league learning is introduced for agents to explore the environment collaboratively with fast convergence and robustness. The article "Intelligent charging path planning for IoT network over blockchain-based edge architecture" by Cho *et al.* classifies the indoor charging planning problem and designs the application of four metaheuristic algorithms. Edge computing and blockchain are adopted to guarantee the finding speed and trustworthiness of charging paths.

D. Novel Blockchain-Based Applications

The eight articles in the fourth group introduce various novel blockchain-based applications subdivided into the following two areas.

1) Design of Platform/System for Blockchain-Based Application: "A blockchain-based containerized edge computing platform for the Internet of Vehicles" by Cui *et al.* proposes a blockchain-based containerized edge computing platform called CUTE, which is designed to provide low-latency computing services over the Internet of Vehicles, and blockchain technology is used to improve network security. Hassija *et al.*, in "A blockchain and edge-computing-based secure framework for government tender allocation," exploit a secure and transparent framework for government tenders. The Schnorr CoSi protocol is used to design a transparent and optimal system for the workflow. To tackle the challenge of security risk of LoRa gateways, Hou *et al.*, in "Design and prototype implementation of a blockchain-enabled LoRa system with edge computing," propose HyperLoRa, a blockchain-enabled LoRa system with edge computing, which uses the open-source hyperledge fabric. Xu *et al.*, in "A blockchain-enabled energy-efficient data collection system for UAV-assisted IoT," propose a blockchain-enabled UAV-assisted IoT application framework, where blockchain and charging coins ensure that each transaction is recorded and each approved behavior is rewarded.

2) Novel Blockchain-Based Applications Specifically for Edge Intelligence: "Boosting edge intelligence with collaborative cross-edge analytics" by Jin *et al.* shows how to jointly optimize input data and task placement for cross-edge collaborative analysis to reduce query response time and network traffic cost. By improving the classic SRPT policy, an effective stream scheduling mechanism is developed for the intermediate data transfer of competing queries. "STEC-IoT: A security tactic by virtualizing edge computing on IoT" by Zhang *et al.* proposes an architecture with virtualized edge nodes to improve computer security. Specifically, this architecture divides edge nodes and abstracts the edge network into virtual networks. A security mechanism is proposed and the security levels of the nodes are measured. The data transmission process is modeled as a virtual network mapping model. Ayaz *et al.*, in "A Proof-of-Quality-Factor (PoQF)-based blockchain and edge computing for vehicular message dissemination," propose a decentralized blockchain-based consensus algorithm, PoQF. A voting-based validation process and a competitive relay selection process based on the probabilistic prediction of channel quality are considered. The bounds of failure and latency in message validation are proved theoretically. The block generation throughput, asymptotic latency, security, and communication complexity of PoQF consensus are analyzed. The article "Offloading time optimization via Markov decision process in mobile-edge computing" by Yang *et al.* investigates an MEC system that supports various radio access technologies. Considering the mobility of devices and the heterogeneity of edge servers jointly, an optimal offloading node selection strategy is formulated to minimize the offloading time.

In conclusion, we would like to thank all the authors who submitted their research articles to our special issue. We highly appreciate the contributions of the reviewers for their constructive comments and suggestions. We would also like to acknowledge the support and guidance from the Editor-in-Chief and editorial staff members.

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