Guest Editorial Emerging Computing Offloading for IoTs: Architectures, Technologies, and Applications

BILLIONS of Internet of Things (IoT) devices, e.g., sensors and RFIDs, are arising around us providing not only computing-intensive, but also delay-sensitive services, ranging from augmented/virtual realities to distributed data analysis and artificial intelligence. Notably, the low response latency for IoT services is achieved at the cost of computing complexity that far exceeds the capabilities of IoT devices. To feed this trend, multiple computing paradigms are emerging, such as mobile transparent computing (TC), edge computing, and fog computing. These paradigms employ more resourceful edge devices, e.g., small-scale servers, smart phones, and laptops, to assist the low-end IoT devices. By offloading the computing-intensive tasks to the edge devices, it is expected to converge the data collection at IoT devices and the data processing at edge devices to provision computing-intensive and delay-sensitive services. However, many issues remain in the application of computing offloading which impede its flourishing in IoTs. To name a few, what are the killer APPs that need computing offloading for performance boost? How to partition an encapsulated APP into offloadable code blocks for remote loading? How to determine which code blocks or computing tasks should be offloaded to edge servers? How to customize the communication protocol to guarantee the coherence of computation offloading?

The response to our Call for Papers on this special issue was enormous, with 135 articles submitted from around the world. During the review process, each paper was assigned to and reviewed by multiple experts in the relevant areas, with a rigorous two-round review process. Thanks to the great support of the Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL, Dr. Xuemin (Sherman) Shen, we were able to accept 45 excellent articles covering various aspects of computation offloading in IoTs. In the following, we will introduce these articles and highlight their main contributions.

In "Power Constrained Edge Computing With Maximum Processing Capacity for IoT Networks," the authors propose a resource allocation policy to maximize the available processing capability for mobile edge computing (MEC)-enhanced IoT networks, while considering the constrained power and unpredictable tasks. The authors design a binary-search water-filling algorithm for efficient power allocation, and a suboptimal algorithm for subcarrier assignment.

In "Secrecy-Based Delay-Aware Computation Offloading via Mobile Edge Computing for Internet of Things," the authors investigate the delay-aware computation offloading via MEC for IoTs. To address the secrecy outage caused by the eavesdropper's overhearing and minimize the overall delay requirement of the IoT devices, the authors formulate a joint optimization of the secrecy provisioning, computation offloading, and radio resource allocation. In addition, an efficient algorithm was designed to compute the optimal computation offloading solution. Specifically, the authors propose a device selection algorithm based on optimal computation offloading decision.

In "LAMANCO: A Lightweight Anonymous Mutual Authentication Scheme for N-Times Computing Offloading in IoT," the authors study private and secure mutual authentication between users in the IoT–Edge–Cloud hierarchical architecture. To address this issue, the authors propose a lightweight anonymous mutual authentication scheme to enable N-times computing offloading (LAMANCO), using the smart card as token and the edge device as a security proxy. The proposed scheme protects the IoT system from denial of services (DoS) attacks by using one-way hash function and MAC function.

In "Offloading-Assisted Energy-Balanced IoT Edge Node Relocation for Confident Information Coverage," the authors investigate the confident information coverage (CIC)-based edge server relocation (CICENR) issue in IoT systems. To handle the CICENR issue, the authors propose the CIC-based direct replacement approach (CIC-DRA) and an offloading-assisted energy-balanced edge node relocation approach (CIC-OAEBA), which can time-efficiently detect coverage holes and schedule to offload the communication-intensive and computing-intensive tasks from IoT nodes to edge servers.

In "Toward Efficient Transparent Computing for IoT Apps by On-Chip Kernel Offload," the authors study the problems of performance and energy optimization of GPUs on TC for IoTs. To deal with these issues, the authors propose the kernel-level offloading solution FuncShare, which enables unmodified Android and Linux-based TC applications to utilize not only application functionalities but also system functionalities across devices.

In "Folo: Latency and Quality Optimized Task Allocation in Vehicular Fog Computing," the authors study the problem of latency and quality-optimized task allocation in vehicular fog computing (VFC) that contains mobile fog nodes. With constraints on service latency, quality loss, and fog capacity, and the concern of task allocation across stationary

Digital Object Identifier 10.1109/JIOT.2019.2921217

and mobile fog nodes, the problem is formulated into a joint optimization problem. Moreover, the authors propose an event-triggered dynamic task allocation (DTA) framework using linear programming-based optimization (LBO) and binary particle swarm optimization (BPSO) to leverage a tradeoff between service latency and quality loss.

In "Theoretical Analysis on Edge Computation Offloading Policies for IoT Devices," the authors study how to offload computation-intensive tasks to their assigned edge computing servers with guaranteed response time and energy consumption of IoT devices. To address this issue, the authors propose a multiqueue model to explore the performance gain obtained by offloading the computation tasks from IoT devices to the assigned edge computing server. Especially, the authors take locality-first policy and probability-based policy into consideration, and propose an analytic solution of the task mean response time and energy consumption at both the IoT devices and edge computing server.

In "Fast Service Migration Method Based on Virtual Machine Technology for MEC," the authors study the problem of offloading tasks from lightweight mobile devices to edge nodes. To improve user experiences, the authors combine remote loading and redirection to accelerate the service migration. By tracing historic access patterns, the proposed method first generates a loading request list that locates the core codes in the image file of service applications. The core codes can then be prefetched and cached automatically. Especially, edge nodes can continuously load the remaining codes in the image file to avoid the potential UI lagging caused by incomplete service migration. Once the image file is completely migrated, the file will be reconstructed. The running virtual machine (VM) then switches data access to the merged image file, and thus significantly reduces the loading time of VM-based applications.

In "Signature Gateway: Offloading Signature Generation to IoT Gateway Accelerated by GPU," to reduce the burden of sensor nodes to generate signatures, the authors propose an IoT architecture that offloads the digital signature generation to a nearby signature gateway equipped with a GPU accelerator. The authors investigate the communication process for signature offloading and optimize the implementations for RSA in the signature gateway and evaluate the performance of two different ways to implement modular exponentiation in RSA, namely residue number system (RNS) and multiprecision Montgomery multiplication (MPMM).

In "Distributed Energy Management for Multi-User Mobile-Edge Computing Systems With Energy Harvesting Devices and QoS Constraints," the authors study the energy-efficiency issue in a multiuser MEC system with energy harvesting (EH) devices. To address this issue, the authors propose a resource allocation policy to minimize system power consumption, while considering the unpredictability of the EH and the quality of service (QoS) and design an online algorithm based on the Lyapunov optimization method, which only uses current states of the mobile users and does not depend on the system statistic information. In order to reduce the system computational complexity, the authors propose a distributed algorithm based on the alternating direction method of multipliers (ADMM).

In "IoT Platforms for the Internet of Production," the authors introduce available commercial IoT platforms and information systems. The authors first give an overview of the Internet of Production reference framework. In this framework, the paper compares the selected IoT platforms in terms of their features and functionalities. This general framework and the representative reference architecture may help companies and software vendors to implement the Internet of Production reference architecture by creating an IoT platform.

In "Fog/Edge Computing-Based IoT (FECIoT): Architecture, Applications, and Research Issues," the authors survey the state-of-the-art IoT literature over the period 2008–2018 and propose the FECIoT which covers the enabling technologies, services, and open research issues. The survey progresses from basic to more advanced concepts within the IoT domain. Furthermore, it shows how FECIoT can be deployed in real-life scenarios, such as intelligent transportation systems, smart grid, and healthcare.

In "Optimized Computation Offloading Performance in Virtual Edge Computing Systems via Deep Reinforcement Learning," the authors propose an optimal computation offloading policy by modeling offloading selection problem as a Markov decision process (MDP), with the objective to maximize long-term utility performance. The authors propose a double deep Q-network-based strategic computation offloading algorithm to learn the optimal policy without having *a priori* knowledge of network dynamics, while breaking the curse of high dimensionality.

Computation offloading in ultradense IoT networks is envisioned to be an effective solution that reduces the conflict between computing-intensive applications and resource-constrained IoT mobile devices. In "Energy-Aware Computation Offloading and Transmit Power Allocation in Ultra-Dense IoT Networks," the authors study the energy-aware task offloading problem with multiple edge servers in ultradense IoT networks and propose an iterative searching-based task offloading scheme to jointly optimize task offloading, computational frequency scaling, and transmit power.

One important issue in edge computing is how to improve performance for mobile devices. In "A Maximum Cache Value Policy in Hybrid Memory-Based Edge Computing for Mobile Devices," the authors propose an efficient cache management policy, which maximizes cache value to minimize memory access cost in a phase-change memory/dynamic random access memory hybrid main memory platform.

In "Energy Efficient Data Collection in Large-Scale Internet of Things via Computation Offloading," the authors propose a new clustering compressed data collection scheme to collect and reconstruct the sensed data in large-scale IoT. The authors model the data reconstruction problem as a group sparse problem, which is solved by using an ADMM-based algorithm. The performance of the proposed scheme is evaluated through experiments with real data sets.

In "On Data Sovereignty in Cloud-Based Computation Offloading for Smart Cities Applications," the authors design a two-level cryptographic approach location-based encryption of user data by introducing an additional encryption layer to the existing security mechanism and propose a localization

approach to obtain a location statement upon which the decryption key is built. Furthermore, the authors propose a localization approach for cloud users by authenticating location claims via ping measurement of geo-location and IoT devices in the smart city infrastructure, based on the computation of mutual distances with references using the received signal strength indicator (RSSI) technique.

Maritime mobile cloud network is the product of the continuous development of cloud computing technology and mobile Internet technology. In "Multivessel Computation Offloading in Maritime Mobile Edge Computing Network," the authors study the issue of computation task offloading for vessel terminals, with the objective to minimize the energy consumption of vessel terminals and the execution delay of computation task. The authors propose a multivessel computation offloading algorithm based on the improved Huangarian algorithm in maritime MEC network.

In "Toward Improved Offloading Efficiency of Data Transmission in the IoT-Cloud by Leveraging Secure Truncating OFDM," the authors propose a spectrum-efficient scheme named secure truncating orthogonal frequency division multiplexing (STOFDM) to support massive data transmission in IoT network, which releases the limit of bandwidth between the IoT devices and the cloud server, while providing secure characteristic.

With the explosion of smart devices and the gradual maturation of mobile systems, Mobile CrowdSensing (MCS) is playing a more and more important role in daily life. In "Diffusion Kalman Filter With Quantized Information Exchange in Distributed Mobile Crowdsensing," the authors propose a distributed MSC architecture to offload the computing and storage burden from traditional MCS architecture. Then, the authors propose a diffusion Kalman filtering algorithm with quantized information exchange to address the issues caused by limited communication resources in the dynamic real-time estimation.

In "Geomagnetism-Based Indoor Navigation by Offloading Strategy in NB-IoT," the authors design a geomagnetism-based indoor navigation system without the structure map of buildings by applying offloading strategy in narrow-band IoT. The authors divide indoor navigation into two parts: 1) the construction of a signal fingerprint database and 2) the user navigation. First, the navigator carries out the signal acquisition of the navigation route and transfers the original signals to a cloud server so as to construct the fingerprint database. Second, users can choose online navigation or offline navigation according to the actual situation.

In "A Truthful Reverse-Auction Mechanism for Computation Offloading in Cloud-Enabled Vehicular Network," the authors establish a novel computation offloading marketplace in vehicular networks to encourage vehicles to share resources between each other, while considering user selfishness. The authors formulate a VCG-based reverse auction mechanism utilizing integer linear programming. To address the high-computational complexity of linear programming, the authors further develop an efficient unilateral-matching-based mechanism to get satisfactory suboptimal solutions.

In "Achieving Differentially Private Location Privacy in Edge-Assistant Connected Vehicles," the authors introduce the concept of edge assistant connected vehicles. Furthermore, considering the location privacy issue, the authors propose a novel differentially privacy-preserving location-based service usage framework that provides an adjustable privacy protection solution to balance the utility and privacy.

In "Fog-Based Computing and Storage Offloading for Data Synchronization in IoT," the authors propose a new architecture for data synchronization based on fog computing. To decrease the communication cost and reduce the latency, the authors design a differential synchronization algorithm, and then extend the method by introducing Reed–Solomon code to enhance the secure performance of the architecture.

In "Joint Computation and Communication Cooperation for Energy-Efficient Mobile Edge Computing," the authors propose a novel user cooperation approach in both computation and communication for MEC systems to improve the energy efficiency for latency-constrained computation. A basic three-node MEC system consisting of a user node, a helper node, and an access point (AP) node attached with an MEC server is introduced, in which two different computation offloading models, namely the partial and binary offloading, are considered, respectively. Finally, the authors develop an efficient four-slot transmission protocol to enable the joint computation and communication cooperation for improved computation capacity and energy efficiency at both the user and helper,

In "An Incentive Mechanism Combined With Anchoring Effect and Loss Aversion to Stimulate Data Offloading in IoT," the authors propose an incentive mechanism comprising the anchoring effect and loss aversion on offloading (AELAO). The AELAO uses anchoring effect (i.e., the influence of referencing a user's decision) and loss aversion (i.e., consequences become more intolerable when facing the same losses and benefits) to be an effective incentive mechanism for the APs. The authors introduce two new concepts called time pressure and regret value. Based on APs' loss aversion, time pressure can encourage them to participate in data offloading as soon as possible within the given time limit.

In "T-REST: An Open-Enabled Architectural Style for the Internet of Things," the authors propose an extension of the REST architectural style, named Things-REST (T-REST), which is an open-enabled ecosystem allowing third-party developers to create and update functions of deployed devices dynamically. They design a novel event-triggering mechanism to decouple the tight coupling of front-end content accesses and back-end computations for resources. Furthermore, the authors implement a reference prototype, named T-REST engine, to verify the proposed architecture with the open-enabled style, distributed semantics, and computing offloading features.

In "Deep PDS-Learning for Privacy-Aware Offloading in MEC-Enabled IoT," the authors identify a new privacy vulnerability caused by the wireless offloading feature of MEC-enabled IoT. To address this vulnerability, an effective privacy-aware offloading scheme is developed based on a newly proposed deep post-decision state (PDS)-learning algorithm. The proposed deep PDS-learning algorithm allows

the IoT devices to learn a good privacy-aware offloading strategy much faster than the conventional deep Q-network by exploiting extra prior information.

In "Green Large-Scale Fog Computing Resource Allocation Using Joint Benders Decomposition, Dinkelbach Algorithm, ADMM, and Branch-and-Bound," the authors investigate the green fog computing by maximizing the network utility function considering energy efficiency with the constraints of power and interference, which is formulated as a large-scale mixed integer nonlinear programming problem. In addition, an algorithm framework is designed to solve the problem in a distributed and parallel manner, whose outer loop is based on the Benders decomposition and the inner loop is handled by the ADMM algorithm. For the master problem, the authors propose a centralized branch-and-bound algorithm to deal with the complexity.

Transparent Computing is a promising technique that makes lightweight devices process even large-size applications. In "Offloading Delay Constrained Transparent Computing Tasks With Energy-Efficient Transmission Power Scheduling in Wireless IoT Environment," the authors allow the TC IoT devices to offload some tasks to servers, since wireless IoT devices are usually powered by batteries, having limited energy resources. They propose a two-step approach aiming at minimizing the energy consumption of the IoT device while satisfies the delay constraint, which first studies the offloading decision problem and then investigates the transmission power scheduling problem. The authors propose a heuristic decision-making algorithm and optimal power scheduling algorithm, respectively.

To study the application deployment with multilevel services (ADMS) problem, in "Resource Provisioning in the Edge for IoT Applications With Multilevel Services," the authors formulate the ADMS problem as an optimization problem with the aim of minimizing the overall deployment cost under the latency/computation/storage/bandwidth requirements and the infrastructure capacity limitations. They design a workflow-based heuristic algorithm called AMS, which can determine how many VMs should be placed for each type of service and where to place them and support the services to scale up or scale down on demand in real time.

Content caching has brought huge potential for the provisioning of nonsafety-related infotainment services in future vehicular networks. In "A Q-Learning-Based Proactive Caching Strategy for Non-Safety Related Services in Vehicular Networks," the authors study the problem that caching services considering both the mobility of vehicles and storage could incur increased latency and considerable cost due to the cache size needed in RSUs. They model the problem using MDPs and propose a heuristic Q-learning solution together with vehicle movement predictions based on a long short-term memory network.

In "FEMTO: Fair and Energy-Minimized Task Offloading for Fog-Enabled IoT Networks," the authors study the fair offloading among multiple FNs while maintaining a satisfactory energy efficiency, which is of great significance for the sustainability of the fog-enabled IoT networks, especially in the scenarios with battery-powered FNs. They propose a fair and energy-minimized task offloading (FEMTO) algorithm based on a fairness scheduling metric, taking three important characteristics into consideration, which include the task offloading energy consumption, the FN's historical average energy, and the FN priority.

In "ERP: Edge Resource Pooling for Data Stream Mobile Computing," the authors propose a novel edge resource pooling framework, in which a massive crowd of devices at the network edge exploit device-to-device (D2D) collaboration for pooling and sharing computation resource with each other, toward real-time and efficient computation offloading. They propose a greedy heuristic approach based on the classical maximum network flow problem, and thus to schedule the task offloading in a cost-efficient manner. In addition, the authors propose a decentralized task offloading scheme, in which IoT devices communicate and determine D2D offloading strategy locally.

In "An Energy-Aware Offloading Framework for Edge-Augmented Mobile RFID Systems," the authors study computing offloading in radio frequency identification (RFID) systems built with mobile readers and analyze the energy consumption characteristics of different components in mobile RFID systems, based on which the authors propose a framework to perform energy-aware offloading for such systems. They illustrate how the proposed framework can help offload computational intensive tasks to edge servers to save energy consumption on mobile readers while satisfying the constraint on total execution time.

In "Game Theoretical Secure Caching Scheme in Multihoming Edge Computing-Enabled Heterogeneous Networks," the authors propose a novel secure caching scheme in heterogeneous networks for multihoming users. They design a trust mechanism to verify the reliability of each edge computing-enabled small cell base station (ECSBS), and propose a Chinese remainder theorem (CRT) to guarantee the integrity of cached contents and preserve the privacy of mobile users. The authors investigate the interactions among mobile users and ECSBSs by Stackelberg game, where the trusted ECSBSs are selected to provide caching space for mobile users with multihoming access.

In "Deep Belief Network for Meteorological Time Series Prediction in the Internet of Things," the authors investigate a hybrid neural network based on a deep belief network model to facilitate time series predictions for the IoT. They integrate both a deep belief network and a recurrent neural network with the gated recurrent unit as the activation unit. For specific, the authors first implement the unsupervised pretraining through the deep belief network and then supervise the curve fitting using the recurrent neural network. Finally, they learn the hybrid neural network and can make predictions.

In "Dynamic Computation Offloading in Edge Computing for Internet of Things," the authors formulate the computation offloading as an optimization problem to minimize the offloading cost while providing performance guarantees. They propose a dynamic computation offloading algorithm (DCOA), which decomposes the optimization problem into a series of subproblems and solves these subproblems concurrently in an online and distributed way. The authors present theoretical

analysis which demonstrates that DCOA can achieve the tradeoff between offloading cost and performance.

In "Learning-Based Privacy-Aware Offloading for Healthcare IoT With Energy Harvesting," the authors propose a reinforcement learning (RL)-based privacy-aware offloading scheme to help healthcare IoT devices protect both the user location privacy and the usage pattern privacy. The scheme uses transfer learning to reduce the random exploration at the initial learning process and applies a Dyna architecture that provides simulated offloading experiences to accelerate the learning process. In addition, a PDS learning method is proposed to further improve the offloading performance by using the known channel state model.

In "Cooperative Edge Computing With Sleep Control Under Nonuniform Traffic in Mobile Edge Networks," the authors propose an online optimization strategy of MEC server (MECS) computation task offloading with sleep control scheme to minimize the long-term energy consumption of the MECS network. They first formulate the energy optimization problem under delay constraint which considers both the radio and computation resources, and then propose a Lyapunov-based approach to convert the long-term optimization problem to a per-slot optimization problem which only requires information of current time slot. The authors propose an online offloading algorithm to make decisions in each time slot and, finally, evaluate the system performance and analyze the impacts of several key parameters.

In "Joint Load Balancing and Offloading in Vehicular Edge Computing and Networks," the authors study the offloading problem where all vehicles offload their tasks to the same VEC server, which will limit the performance gain due to overload. They propose to integrate load balancing with offloading, and study resource allocation for a multiuser multiserver VEC system to address the problem. The authors first formulate the joint load balancing and offloading problem as a mixed integer nonlinear programming problem to maximize the system utility, then decouple the problem as two subproblems. They develop a low-complexity algorithm to jointly make VEC server selection and optimize offloading ratio and computation resource.

In "Decentralized and Revised Content-Centric Networking-Based Service Deployment and Discovery Platform in Mobile Edge Computing for IoT Devices," the authors present a decentralized and revised content-centric networking (CCN)-based MEC service deployment/discovery protocol and platform, by which the MEC nodes can deploy or discover the requested service instances in the proximity of IoT devices to reduce transmission delay. They organize a gateway in every area according to a three-tiered hierarchical MEC network topology and revise CCN to help the service provider deploy their service on MEC node and assist MEC node discover services in neighboring nodes. The authors also present a mathematical model to calculate the round-trip time to guarantee QoS.

In "Toward a Heterogeneous Mist, Fog, and Cloud-Based Framework for the Internet of Healthcare Things," the authors study how to maintain high QoS in terms of faster responsiveness and data-specific complex analytics. They propose a five-layered heterogeneous mist, fog, and cloud-based Internet of Healthcare Things (IoHT) framework, which is capable of efficiently handling and routing (near-)real-time as well as offline/batch mode data. The proposed framework ensures optimal resource allocation and efficient resource utilization by employing software-defined networking and link adaptation-based load balancing.

In "Joint Resource Allocation for Latency-Sensitive Services Over Mobile Edge Computing Networks With Caching," the authors jointly consider computation offloading, content caching, and resource allocation as an integrated model, which is formulated as a mixed integer nonlinear programming (MINLP) problem, to minimize the total latency consumption of the computation tasks. They design an asymmetric search tree and improve the branch and bound method to obtain a set of accurate decisions and resource allocation strategies. They introduce the auxiliary variables to reformulate the proposed model and apply the modified generalized benders decomposition method to solve the MINLP problem in polynomial computation complexity time.

In "Dynamic Edge Computation Offloading for Internet of Things With Energy Harvesting: A Learning Method," the authors model the computation offloading process as an MDP so that no prior statistic information is needed to cope with the problem of effective computation offloading scheme design for the EH MEC system. To address the large time complexity challenge of learning algorithms, they first introduce an after-state for each state-action pair so that the number of states in the formulated MDP is largely decreased, and then introduce a polynomial value function approximation method to accelerate the learning process. In addition, the authors propose an after-state RL algorithm for the formulated MDP to obtain the optimal offloading policy, and also present several analytical properties of the offloading policy to provide efficient instructions for real MEC systems.

The Guest Editors would like to express our gratitude to the authors for their excellent contributions to this special issue. We also would like to thank all the reviewers who dedicated their efforts in reviewing the papers, and for their valuable comments and constructive suggestions to significantly improve the quality of the articles. Special thanks are due to the Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL, Dr. Xuemin Shen, for his help in the publication process. We hope that the special issue can serve as a good reference for scientists, engineers, and academicians in the area of computation offloading in IoTs.

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