# Guest Editorial
# Special Issue on Wireless Energy Harvesting for Internet of Things

THE UBIQUITOUS sensor-rich mobile devices (e.g., smartphones, wearable devices, and smart vehicles) have been playing a vital role in the evolution of the Internet of Things (IoT), which bridges the gap between digital and physical spaces. The powerful computing/communication capacities, huge population, and inherent mobility make mobile device networks a much more flexible and cost-effective IoT solution than traditional wireless sensor networks. However, the energy issue of mobile terminals poses significant challenges to the widespread use of IoT: not only the mobile terminals have short lifetime with the proliferation of mobile applications but also the current networking and communication technologies are not adequately taking the energy efficiency into account. Therefore, the sustainable issue of IoT has attracted considerable attention from both academia and industry. Wireless energy harvesting (EH), and transfer technology was recently proposed as an effective mean to address this issue. It enables the mobile terminals to harvest energy from the ambient environment to prolong its battery. Although some forms of EH have been applied to WSNs, networking and communication solutions must be redesigned for wireless powered IoT with massive number of mobile terminals.

In light of the increasing interest of these topics, this Special Issue will focus on, but will not be limited to, the following subjects of interest: simultaneous wireless information and power transfer (SWIPT) in IoT, secure IoT with wireless energy harvesting, relay-based wireless energy harvesting IoT systems, MAC protocols for wireless energy harvesting and transfer in IoT, economics of wireless energy and data transmission, energy efficient transmissions and network architecture, scheduling and optimization of both users for energy transfer and of data packets, hardware design and prototyping for SWIPT applications in IoT, interference aided wireless energy harvesting, waveform design and optimization for wireless power transfer, optimal control for wireless energy transfer and harvesting, wireless power enabled machine-to-machine and device-to-device communications, and optimal wireless power transfer enabled IoT transceiver architectures.

95 papers were submitted from around the world in response to our Calls for Papers. 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 courtesy of the Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL, Dr. Xuemin (Sherman) Shen, we are able to accept 24 excellent papers covering various aspects of "Wireless Energy Harvesting for Internet of Things." We are also glad to note that many authors of these papers have industry background. In the following, let us introduce these papers and highlight their main contributions.

In "Design and Evaluation of 'BTTN': A Backscattering Tag-to-Tag Network," the authors developed a working prototype of backscattering tag-to-tag network which enabled the passive tags to communicate with each other via backscatter modulation of an external RF excitation signal. The innovative tag architectures and a novel multiphase backscatter modulation technique was developed to overcome challenges caused by the low sensitivity and the lack of active demodulator on passive tags. The hardware and the firmware were developed to test its performance.

In "An On-Demand Energy Requesting Scheme for Wireless Energy Harvesting Powered IoT Networks," an on-demand energy requesting mechanism for improving the delay performance of a wireless EH-powered IoT network was proposed. Such a mechanism was evaluated by using discrete time Markov chain models in terms of packet delay, network throughput, packet loss probability, and packet reliability ratio.

In "Multi-Tone Excitation Analysis in RF Energy Harvesters—Considerations and Limitations," the authors evaluated the performance of a voltage double rectifier under multitone excitation which is of great importance for RF EH. Based on their simulations and analyses, it is evident that the application of multiple tones results in a lower average output dc power compared with the single-tone case with the same input power.

In "RF Energy Transfer Channel Models for Sustainable IoT," a new channel model was proposed to accurately characterize the harvested dc power at the receiver (RX). Various factors were considered in the proposed model including the effects of nonline of sight component along with the other factors, such as, radiation pattern of transmit and receive antennas, losses associated with different polarization of transmitting field, and efficiency of power harvester circuit.

In "Energy Sustainable IoT With Individual QoS Constraints Through MISO SWIPT Multicasting," the authors considered a multiple-input single-output multicasting IoT system comprising of a multiantenna transmitter (TX) simultaneously transferring information and power to low power and data hungry IoT RXs. The problem of joint design of TX precoding

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and IoT PS ratios were studied with individual QoS requirements considered. A nonconvex optimization problem was formulated and solved.

In "Energy Allocation and Utilization for Wirelessly Powered IoT Networks," the authors solved two problems, i.e., the sensor energy utilization policies and the power allocation among sensors by maximizing the total data throughput of the system. Markov decision process was utilized to formulate the problems, and algorithms were proposed to solve these two problems.

In "Adaptive Wireless-Powered Relaying Schemes With Cooperative Jamming for Two-Hop Secure Communication," a two-hop relay network was considered with an eavesdropper who can overhear the relaying signal. A jamming noise was adopted, and the relay node can harvest energy from both the source signal and the jamming noise. Two adaptive relaying protocols were proposed to achieve a balance between signal processing and EH.

In "A New Relay Policy in RF Energy Harvesting for IoT Networks—A Cooperative Network Approach," three scenarios of the EH relay network were considered. The optimal relay policy in these scenarios was analyzed. The effect of EH on performance metrics was investigated to find the optimum relay policy.

In "On Dual-Path Energy-Harvesting Receivers for IoT With Batteries Having Internal Resistance," the impact of the internal resistance at the EH RX was analyzed. The dual-path architecture and its optimal battery management scheme were presented. Based on such a scheme, a throughput maximization problem was studied.

In "Simultaneous Wireless Information and Power Transfer for Internet of Things Sensor Networks," the authors proposed a novel strategy for SWIPT in which the TXs have the option to either send a private or a common message. The private message is recovered only by a designated IoT RX while common messages are recovered by all the RXs. Numerical simulations demonstrated that the proposed schemes significantly outperform conventional schemes.

In "Accumulate Then Transmit: Multi-User Scheduling in Full-Duplex Wireless-Powered IoT Systems," the accumulate-then-transmit framework was evaluated in an EH-powered IoT system. A new throughput-oriented scheduling scheme was proposed based on the accumulate-then-transmit framework. The outage probability and average throughput were derived for proposed schemes.

In "Multiband Ambient RF Energy Harvesting Circuit Design for Enabling Batteryless Sensors and IoTs," a well-designed circuit was developed to operate on multiple different RF cellular and ISM bands. Realistic data on ambient RF signal strength was analyzed. The proposed adjustable circuit was designed to harvest from LTE 700 MHz, GSM 850 MHz, and ISM 900 MHz bands.

In "Outage Performance Analysis of Wireless Energy Harvesting Relay-Assisted Random Underlay Cognitive Networks," the authors analyzed the outage probability in wireless EH relay-assisted underlay cognitive networks. Efficient relay selection strategy was proposed. And the impacts of related network parameters on the outage probability is explored.

In "A 3-D Energy-Harvesting-Aware Routing Scheme for Space Nanosatellite Networks," the authors proposed a 3-D routing scheme for solar-powered nanosatellite network. EH capabilities and geographic positions of neighboring nanosatellites were taken into consideration in such scheme.

In "Robust Transmission Power Management for Remote State Estimation With Wireless Energy Harvesting," remote state estimation and EH were considered jointly. A robust transmission power split algorithm was provided to minimize the cost function for the worst-case channel state.

In "Microservices Scheduling Model Over Heterogeneous Cloud-Edge Environments As Support for IoT Applications," the authors proposed a new model for scheduling microservices over heterogeneous Cloud-Edge environments. Such a model used a particular mathematical formulation for describing an architecture that includes heterogeneous machines that can handle different microservices. It was founded that some very simple scheduling algorithms may outperform some others in given situations.

In "Distributed Wireless Power Transfer System for Internet-of-Things Devices," a distributed wireless power transfer system was proposed, which included a number of multiantenna power beacons that are distributed over space and send out wireless power to charge IoT devices. It was shown that the distributed wireless charging is advantageous in terms of the coverage probability with the aid of the optimal distributed beamforming.

In "Incentive Mechanism Design for Wireless Energy Harvesting-Based Internet of Things," the problem of how to motivate the energy access points to transfer energy to IoT devices. A practical scenario with limited information was considered. The existing Stackelberg game-based approach with complete information was extended to the realistic scenario by using a contract theory-based framework.

In "Energy-Efficient SWIPT in IoT Distributed Antenna Systems," the authors studied the energy efficiency in SWIPT-based distributed antenna (DA) system. In the considered system, power splitting was applied at IoT devices to coordinate the EH and information decoding processes by varying transmit power of DA ports and PS ratios of IoT devices. An efficient suboptimal algorithm was proposed to solve the efficiency maximization problem.

In "Energy-Latency Tradeoff for Energy-Aware Offloading in Mobile Edge Computing Networks," to investigate the tradeoff between energy consumption and latency, the authors presented an energy-aware offloading scheme, which jointly optimizes communication and computation resource allocation under the limited energy and sensitive latency. An iterative search algorithm was proposed to minimize the energy consumption and latency.

In "DTER: Optimal Two-Step Dual Tunnel Energy Requesting for RF-Based Energy Harvesting System," a two-step dual tunnel energy requesting (DTER) strategy was proposed to minimize the energy consumption on both the EH device and the power beacons. Both offline and online scenarios are considered in the second step of DTER. To solve the nonlinear optimization problem of the offline scenario, we convert the design of offline optimal energy requesting problem into a classic shortest path problem.

In "A Joint Energy Replenishment and Data Collection Algorithm in Wireless Rechargeable Sensor Networks," a joint energy replenishment and data collection algorithm for WRSNs was proposed. In such an algorithm, the network is divided into multiple clusters based on a $K$-means algorithm. Two wireless mobile chargers were considered in this paper to charge the sensors by visiting the anchor points. A semi-Markov model is proposed for energy prediction, so anchor points can be found.

In "Energy Efficiency Optimization With SWIPT in MIMO Broadcast Channels for Internet of Things," the authors addressed the energy efficiency optimization problem for SWIPT multiple-input multiple-output broadcast channel with time-switching RX design. The original problem with multiple constraints was transformed into a suboptimal min–max problem with a single constraint and multiple auxiliary variables

In "Coordinated Multipoint Based Uplink Transmission in Internet of Things Powered by Energy Harvesting," the authors studied the CoMP uplink transmission to alleviate outage caused by EH of BSs in IoT. Such a problem considered the case that the base stations being powered by EH modules, may keep OFF during recharging, leading to super-frequent handovers for nodes and high network dynamics.

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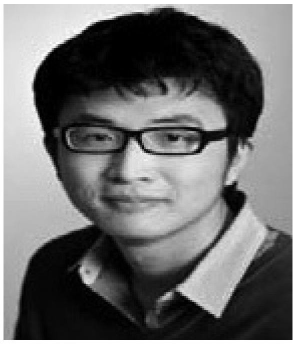

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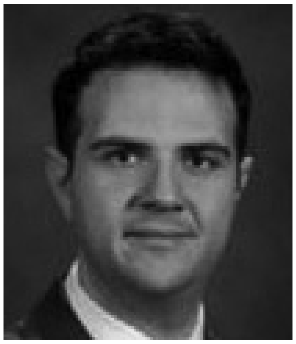

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