Date of current version February 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2895439

EDITORIAL

IEEE ACCESS SPECIAL SECTION EDITORIAL: WIRELESSLY POWERED NETWORKS: ALGORITHMS, APPLICATIONS, AND TECHNOLOGIES

Wireless Power Transfer (WPT) is, by definition, a process that occurs in any system where electrical energy is transmitted from a power source to a load without the connection of electrical conductors. WPT is the driving technology that will enable the next stage in the current consumer electronics revolution, including battery-less sensors, passive RF identification (RFID), passive wireless sensors, the Internet of Things and 5G, and machine-to-machine solutions. WPT-enabled devices can be powered by harvesting energy from the surroundings, including electromagnetic (EM) energy, leading to a new communication networks paradigm, the Wirelessly Powered Networks.

While recent advances in wireless utensils appear to be unlimited, the dependence of their operation on batteries remains as a weakness, mainly because batteries come with a limited lifetime and require a fast charge time to achieve continuous operation. This is where the technologies of WPT become useful, bringing together wireless energy and data transmission. WPT technologies substitute the traditional powering concept, where a cable or a battery is connected to the wireless device, by the transmission of energy over the air in an efficient way to power-up the device.

Wirelessly Powered Networks have recently evolved into a very active research field, as well as a topic of rapid technological progress, emerging practical developments and standardization activities. However, a solid foundational, technological, and applied background is still necessary for Wirelessly Powered Networks to achieve their full potential. The provisioning of relevant technological models, algorithmic design and analysis methods, networking principles, circuit and system design, and application methodologies is a challenging task. This Special Section in IEEE ACCESS invited academic and industrial experts to make their contributions on Wirelessly Powered Networks. It selectively spans a coherent, large spectrum of fundamental aspects of WPT, and will focus on three main thematic pillars and relevant themes: Algorithms, Applications and Technologies.

Our call for papers received an enthusiastic response with 47 high-quality submissions, covering diverse topics on Wirelessly Powered Networks. All articles were reviewed by at least two independent referees. The articles were evaluated for their rigor and quality, and also for their relevance to the theme of our Special Section. We eventually accepted 19 articles for publication, some after multiple revisions. The accepted articles cover a variety of important and challenging topics in the area of Wirelessly Powered Networks and they provide a high geographical diversity, coming from China, Czech Republic, France, Greece, India, Italy, Japan, Korea, New Zealand, Pakistan, Portugal, Russia, Singapore, Spain, UAE, UK and USA.

The accepted articles cover a diverse spectrum of WPT application areas and methods, broadly divided in 4 categories: Internet of Things Networks (7 articles), Wireless Powered Communication Networks (5 articles), Cognitive Radio Networks (2 articles), Simultaneous Wireless Power and Information Transfer (5 articles). Below we present the accepted articles per category.

I. INTERNET OF THINGS (IOT) NETWORKS

The invited article of the Special Section ‘‘On electromagnetic radiation control for wireless power transfer in adhoc communication networks: key issues and challenges,’’ authored by Filios, *et al*., provides a holistic overview of the aspect of electromagnetic radiation (EMR) and its efficient control in WPT-enabled IoT networks. The global perspective of this study is to highlight methods for the effective control of EMR while keeping at high levels the quality of service experienced by users as well as the energy transfer efficiency of WPT. The article investigates the cases of different energy transfer model, such as the scalar model, the vectorial model and the peer-to-peer wireless charging model.

Poveda-Garcia, *et al*., in their article ‘‘Dynamic wireless power transfer for cost-effective wireless sensor networks using frequency-scanned beaming,’’ introduce an adaptive 1D frequency-scanning method for radiative WPT systems in low-power Wireless Sensor Networks. As a proof of concept, a leakywave antenna that scans 1W output RF power in the 2.4 GHz band, is used to power a network covering an area of 1.2 m X 1.2 m. The authors show that any sensor can select the optimum transmission channel, which maximizes the WPT beaming efficiency and thus the transferred DC power. This is accomplished by simply monitoring the Received Signal Strength Indicator as the coordinator performs a scheduled frequency hopping phase.

The article "A novel RF-powered wireless pacing via a rectenna-based pacemaker and a wearable transmit-antenna array," authored by Asif, *et al.*, propose a wearable RF-powered leadless pacing system, which can be implanted directly inside the heart and powered via RF energy, without any batteries or pacing leads. More specifically, the authors have realized a prototype rectenna-based leadless pacemaker (LP), the implant, which consists of an implantable rectenna, charging and pacing circuits as well as the pacing electrodes. Also, a wearable transmit-antenna array was designed, developed, and fabricated for RF energy transmission into the body. In an acute animal study, using ovine models, the proposed leadless pacemaker was implanted at the left ventricular apex by thoracotomy. Using the prototype wearable transmit-antenna array, the prototype leadless pacemaker was powered wirelessly and as a result, leadless pacing was successfully demonstrated in the in vivo ECG results. Besides measuring the efficiency of the rectenna, the computations of Specific Absorption Rate are presented and found to be under the IEEE recommended limits, thus demonstrating that a wearable RF-powered leadless pacing system is realizable with SAR under the safe levels.

Kracek and Svanda, in their article, "Analysis of capacitive wireless power transfer," deal with a general rigorous circuit analysis of a WPT chain, which realizes the WPT with the help of capacitive coupling. They show the derivation of the power transfer efficiency through the chain in question as well as the active power delivered to the appliance terminating this chain. Both the case of the maximal efficiency and the one of the maximal appliance power were treated and conditions for these optima were found in both cases. The appliance power corresponding to the maximal efficiency and the efficiency corresponding to the maximal appliance power were also expressed. The total admittance of the capacitive wireless power transfer chain was calculated. For both optimal conditions, the appliance power and total admittance were written in the normalized form, which enabled to express them as functions of single variable in the same way as the efficiency.

The article "Towards the design of wireless communicating reinforced concrete," authored by Loubet, *et al.*, addresses the concept of a smart-node wireless network designed for structural health monitoring applications. The network architecture is based on a smart mesh composed of sensing nodes and communicating nodes. The sensing nodes are used to implement the so named communicating material/communicating concrete and collect physical data for structural health monitoring purposes. These data are sent to the communicating nodes that interface the smart-node network with the digital world through the Internet. The sensing nodes are batteryless and wirelessly powered by the communicating nodes via a wireless power transmission interface. Experimental results have been obtained for a simplified sensing node using a LoRaWAN uplink wireless communication (from the sensing node to the communicating node) proving that the functionality of the sensing nodes can be controlled wirelessly by using only the wireless power transmission downlink.

Sim, *et al.*, in their article "Mitigation of phase cancellation for efficient decoding and RF energy harvesting in tag-to-tag communications," investigate a phase cancellation problem that occurs in tag-to-tag communication systems. These are systems wherein several tags communicate with each other by backscattering an external constant wave signal. A transmitting tag modulates baseband information onto the reflected signal using backscatter modulation. At the receiving tag, the received signal is superposition of the transmitted signals by the carrier emitter and the transmitting tag. The resulting signal is demodulated using the envelope detector that causes the phase cancellation problem. This problem exists in all tag-to-tag communication systems and largely impacts the reliability and communication range. The authors theoretically analyze and experimentally demonstrate this problem for the tags that use amplitude-shift keying based backscattering. They propose an algorithm for mitigation of the phase cancellation based on the phase rotation control (PRC). Then, they examine the performance of the proposed algorithm through theoretical analysis and computer simulations, and confirm that the proposed algorithm can significantly mitigate the phase cancellation.

The article "Full-duplex wireless powered IoT networks," authored by Kang, *et al.*, studies the WPT-enabled IoT networks, where one hybrid access point with constant power supply communicates with a set of IoT devices. This hybrid access point is assumed to work in a full-duplex mode, which transmits/receives signals to/from these IoT devices simultaneously during the whole frame. The IoT devices are capable of harvesting energy from the received signals broadcast by the hybrid access point. And the harvested energy is used to support the uplink transmission. Since time-division multiple access is used in uplink transmission, one IoT device keeps harvesting energy till its own uplink time slot. The objective of this article is to maximize the total surplus energy, which is defined as the gap between available energy and consumed energy for uplink transmissions, by exploiting the optimal time allocation scheme for each device. A distributed non-cooperative and a bargaining cooperative game-based algorithm are proposed to solve this problem. In addition, the well-known KKT condition approach is adopted as a comparison.

II. WIRELESS POWERED COMMUNICATION NETWORKS (WPCN)

The article "Weighted harvest-then-transmit: UAV-enabled wireless powered communication networks," authored by Cho, *et al.*, proposes an unmanned aerial vehicle (UAV)-enabled WPCN, which consists of a hybrid access point, a UAV, and nodes. The hybrid access point broadcasts energy to all nodes, and the nodes harvest and use the energy for information transmission. However, far-apart nodes from the hybrid access point hardly harvest the energy and they require more energy for the same throughput as near-apart nodes due to distance-dependent signal attenuation, which is called the doubly-near-far problem. To overcome the doubly-near-far problem, the authors propose a weighted harvest-then-transmit protocol. In the proposed protocol, they consider that the channel power gain changes according to the location of nodes, whereas it has remained constant in most conventional networks. The UAV acts as a mobile hybrid access point, where the UAV performs weighted energy transfer and receives information to/from all encountering far-apart nodes with the better channel power gain. For the UAV, they consider the flight path optimization by implementing a regression algorithm in terms of energy efficiency. Under these considerations, they aim to maximize the sum-throughput of all nodes based on the weighted harvest-then- transmit protocol, by using convex optimization techniques. The optimal time allocation is investigated for far-apart nodes and near-apart nodes sequentially, to solve the doubly-near-far problem. Simulation results show that the proposed UAV-enabled WPCN outperforms the conventional WPCN with a fixed H-AP in terms of the sum-throughput maximization.

Huang, *et al.*, in their article "On opportunistic energy harvesting and information relaying in wireless-powered communication networks," introduce a new design of a relay WPCN to improve its throughput performance by opportunistic energy harvesting and information relaying at the relay node. A new protocol, namely, the adaptive harvest- store-forward protocol, is proposed. Then, under the proposed protocol, a throughput maximization problem is formulated to optimize the relay operation mode and resource allocation in a finite time horizon. The formulated problem is coupled over time and, thus, is intractable. To address the intractability, dynamic programming is employed to transform the problem into a series of Bellman equations. Based on the Bellman equations, the optimal decision criteria for the relay operation mode is derived, and a time-coupled optimization problem for the resource allocation is addressed by decoupling into two sub-problems for two adjacent time frames. By solving the sub-problems via convex programming, an optimization policy with causal channel-state information, which can be implemented online in real time, and an optimization policy which is used to reveal the upper bound of the achieved throughput, are achieved. The simulation results verify that the proposed design can yield significant throughput gains over the existing wireless-powered relaying schemes.

The article "Accelerated sampling optimization for RF energy harvesting wireless sensor network" authored by Zhao, *et al.*, proposes a fast rate control algorithm to maximize network utility for energy harvesting in a WPCN. Energy harvesting and channel bandwidth limits are considered together to formulate as a utility maximization problem. Then, an accelerated distributed gradient method is proposed to solve the problem for energy harvesting. Numerical experiments show that the accelerated method achieves faster convergence to the optimal sampling rate under energy and channel constraints than traditional gradient descent methods.

Sudhakara Rao, *et al.*, in their article "RF energy harvesting based multiple access relay systems: a DMT perspective," analyze a multiple-access relay system for WPCNs, where the relay node is powered by RF radiation. Specifically, the focus is on the time-switching based scheme in which the intermediate relay switches between energy harvesting, information decoding, and the information re-transmission. For this system, the authors have characterized the diversity-multiplexing trade-off (DMT) for two variants of energy harvesting-based dynamic decode-and-forward protocols: without feedback and with limited feedback. The impact of energy harvesting duration on the DMT performance has been extensively investigated. The performance of the proposed methods approach the diversity upper bound in the high multiplexing gain regime.

Yang, *et al.*, in their article "Energy efficiency maximization for relay-assisted WPCN: joint time duration and power allocation," study a relay-assisted WPCN, where a hybrid relay node broadcasts radio frequency energy to energy harvesting users and forwards these users' data to a base station in amplify-and-forward (AF) or decode-and-forward (DF) fashions. The joint time duration and power allocation optimization problems for both AF and DF relay-assisted WPCNs are investigated to maximize the energy efficiency of hybrid relay node, which are challenging to solve due to the non-convexity and strong coupling of variables. For the DF relay-assisted WPCN, the authors propose an optimal time duration and power allocation algorithm by decomposing the original problem into three sub-problems, i.e., time duration allocation sub-problem for users' information transfer, time duration allocation sub-problem for hybrid relay node's energy and information transfer, and hybrid relay node's power allocation sub-problem. For the AF rely-assisted WPCN, they propose an iterative algorithm to optimize the transmit power and energy transfer time of the hybrid relay node, by proving the quasi-concavity of the objective function where the optimal time duration allocation has been derived. Simulation results verify that the proposed algorithms can render significant energy efficiency gains, e.g., the performance gains of the proposed algorithms are about 300% and 150% compared with the existing schemes for the AF relay-assisted WPCN and DF relay-assisted WPCN, respectively, when the noise power is relatively large.

III. COGNITIVE RADIO NETWORKS (CRN)

Xu, *et al.*, in their article "Multi-hop cognitive wireless powered networks: outage analysis and optimization," analyze and optimize the outage performance of multi-hop wireless powered CRNs in underlay paradigms. In the suggested model, there are multiple power beacons performing WPT for multiple battery-free secondary users. Correspondingly, the secondary users first harvest energy from the RF signals of beacons and then execute multi-hop cognitive data transmission in the licensed channel concurrently with the primary users. Therefore, the transmit power of the secondary users are subject to the energy causality constraint imposed by WPT and the interference power constraint from multiple primary users. The authors derive and obtain the closed-form exact and asymptotic end-to-end outage probabilities for the multi-hop operation of the network over Rayleigh block fading. Furthermore, they optimize the outage performance by studying the outage minimization problem with respect to the WPT power and the WPT time. Due to the complexity of outage probability, they propose a self-adaptive particle swarm optimization based resource allocation algorithm to jointly optimize the power and time for WPT. Extensive simulations validate the correctness of theoretical analysis and the effectiveness of the proposed optimization algorithm.

The article, ''Secure energy efficiency for noma based cognitive radio networks with nonlinear energy harvesting,'' authored by Wang, *et al*., proposes a non-orthogonal multiple access (NOMA)-based secure scheme for CRNs. In the proposed scheme, the secondary users harvest energy from the radio-frequency signals to securely transmit the secondary privacy information with the NOMA technique. Unlike the conventional ideal linear energy harvesting, the authors employ the practical nonlinear energy harvesting model for energy harvesting. To implement the proposed scheme, the energy transmitter first broadcasts radio-frequency signals to power the secondary users. Then, the secondary users employ the NOMA technique to transmit the uplink privacy information, which is threatened by the eavesdropper. Considering two scenarios: two secondary users and more than two secondary users, the authors first provide comprehensive analysis of the secondary secrecy performances and derive the closed-form expressions of the secrecy outage probability for both scenarios. Following the above analysis, they develop the optimization problems to optimally allocate the time slot and the secondary transmit power such that the minimum secrecy energy efficiency is maximized under the constraints of the transmission security and reliability requirements. A two-stage algorithm is proposed to efficiently solve the above optimization problems. Numerical results are presented to verify the analysis in terms of the secrecy rate and secrecy energy efficiency.

IV. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER (SWIPT)

Mohjazi, *et al*., in their article ''Performance analysis of SWIPT relaying systems in the presence of impulsive noise,'' develop an analytical framework to characterize the effect of impulsive noise on the performance of relay-assisted SWIPT systems. The authors derive novel closed-form expressions for the pairwise error probability considering two variants based on the availability of channel state information, namely, blind relaying and channel state information-assisted relaying. They further consider two energy harvesting techniques, i.e., instantaneous energy harvesting and average energy harvesting. Capitalizing on the derived analytical results, they present a detailed numerical investigation of the diversity order for the underlying scenarios under the impulsive noise assumption. For the case with two relays and the availability of a direct link, it is demonstrated that the considered SWIPT system with blind average energy harvesting-relaying is able to achieve an asymptotic diversity order of less than 3, which is equal to the diversity order achieved by channel state information-assisted instantaneous energy harvesting-relaying. Their results show that placing the relays close to the source can significantly mitigate the detrimental effects of impulsive noise. Extensive Monte Carlo simulation results are presented to validate the accuracy of the proposed analytical framework.

The article ''OFDM based SWIPT for two-way AF relaying network,'' authored by Lu, *et al*., considers a three-node two-way relaying network, where an amplify-and-forward relay helps to forward the information of source nodes by using the energy harvested from the radio frequency signals transmitted from the two source nodes. The source and relay nodes work on half-duplex, which completes the transmission in two phases. Specifically, in the first transmission phase, two source nodes transmit their signals to relay. The received signals at relay will be divided into two subcarrier groups, to perform information decoding and energy harvesting separately. In the second transmission phase, after subcarrier pairing, relay amplifies the received signals then forwards them to the two source nodes with the harvested energy. A joint resource optimization problem, including subcarrier grouping, paring and power allocation, is formulated to maximize the sum transmission rate of source nodes with power constraints. Simulation analyses show that the proposed algorithm outperforms the other two benchmark algorithms and reveal the system performance influence of relay location and total transmission power.

Chen, *et al*., in their article ''Energy efficiency analysis of bidirectional wireless information and power transfer for cooperative sensor networks,'' study the energy efficiency of bidirectional wireless information and power transfer in cooperative sensor networks, where the relay node can decode and forward information from the sensor node to base station, and assist the wireless power transfer from the base station to sensor node. For the power splitting protocol, they propose the optimal joint power allocation scheme to maximize the energy efficiency. For the time switching protocol, the optimal power allocation strategy and optimal time allocation scheme are derived by studying the derivative of the energy efficiency. They also provide simulation results to verify the performance of the proposed schemes for the cooperative sensor networks.

The article ''Multi-dimensional resource allocation for uplink throughput maximization in integrated data and energy communication networks,'' authored by Yang, *et al*., establishes a generic integrated data and energy communication network, by integrating the SWIPT in the downlink transmission of a WPCN, where the user equipment acquires both data and energy from the downlink transmission of a hybrid base station and they upload their own data to the hybrid base station by exploiting the energy harvested during their downlink transmissions. In order to maximize the sum-throughput and the fair-throughput of the user equipment's uplink transmissions, the corresponding multi-dimensional resource allocation scheme is obtained by jointly optimizing the transmit beamformer of the hybrid base station in the spatial domain, by optimizing the time-slot allocation in the time-domain and by optimizing the user equipment's power splitting strategies in the power domain. The original non-convex optimization problem is decomposed and transformed into several convex sub-problems, which have been iteratively solved by exploiting the successive convex approximation based algorithm for obtaining the optimal resource allocation scheme. The optimal initial transmit beamformer is found to significantly reduce the complexity of this algorithm.

Rajaram, *et al.*, in their article, "Receiver design to employ simultaneous wireless information and power transmission for joint CFO and channel estimation," design a new receiver for joint Carrier Frequency Offset (CFO) and Channel Estimation on single-carrier modulations with frequency-domain equalization along with SWIPT implementation for energy harvesting by using the pilot signal. The pilot signal is a highly-energized signal. This is superimposed with the information signal that is used not only to transmit power for energy harvesting purposes, but also to estimate the CFO and channel conditions. The receiver is designed to cope with the strong interference levels in the channel estimation and data detection. The proposed scheme offers a flexible design method and efficient resource utilization.

ACKNOWLEDGEMENTS

We would like to congratulate the authors of the published articles for their contributions. We are confident that this Special Section will be of interest for the readers of IEEE Access. We also hope that it will strengthen the connections between the communities of algorithms, applications and technologies in the field of Wirelessly Powered Networks, eventually fostering further research in this area.

We would like to express our appreciation to all referees, who kindly volunteered their time and expertise to help us curate a high-quality Special Section on this important and timely topic, for their diligence and efforts. We would also like to thank the former IEEE Access Editor-in-Chief, Professor Michael Pecht, as well as the current Editor-in-Chief, Professor Derek Abbott, and the staff members of IEEE Access for their continuous support and guidance.

It has been our great pleasure to organize this Special Section and we sincerely hope you will enjoy reading it.

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