IEEE ACCESS Special Section Editorial: Energy Harvesting and Scavenging: Technologies, Algorithms, and Communication Protocols

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EDITORIAL

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The operation of modern electronic communication devices relies on constant energy sources such as DC power, obtained from AC sources via AC to DC conversion, or small chargeable/replaceable batteries. However, in some cases, providing constant energy sources may not be feasible. Advanced energy harvesting technologies can be used to power up modern day electronic communication devices [item 1) in the Appendix]. These energy harvesting technologies rely on energy sources naturally present in the environment, such as solar energy, wind energy, and heat [item 2) in the Appendix]. Moreover, energy can also be acquired from the movement of different parts of the human body such as legs (walking), heart (beating) and arms (swinging), just to name a few. All these energy harvesting technologies and techniques may satisfy the need of energy for low power communication devices and may enable the charging of electronic mobile devices anywhere and at any time [item 3) in the Appendix].

In this Special Section in IEEE ACCESS, we focus on the most recent advances in several interdisciplinary research areas encompassing the energy harvesting domain. This Special Section has brought together researchers from diverse fields and specializations, such as communications engineering, computer science, electrical and electronics engineering, bio-medical engineering, education sector, mathematics and specialists in the areas related to energy harvesting technologies.

This Special Section includes 15 high-quality articles from leading researchers around the globe. Among those, one is the invited article entitled ''Electric-field energy harvesting from lighting elements for battery-less Internet of Things'' by Cetinkaya et al., which focuses on energy harvesting for Internet of Things (IoT).

The aim of IoT is to connect every device to the Internet. Many of the IoT devices will be battery operated, and so energy is a major concern for smooth operation [item 4) in the Appendix]. Monitoring and replacing the batteries of these thousands of IoT devices would be difficult; therefore, energy harvesting techniques have been proposed to meet their energy demands [item 5) in the Appendix], [item 6) in the Appendix]. Though there exist several energy harvesting techniques, in this article by Cetinkaya et al., authors propose a completely new energy harvesting paradigm i.e., to utilize the ambient electric field present in the vicinity of lighting elements. Authors designed the physical model and circuit diagram along with a prototype to demonstrate their approach. Authors also demonstrated that 1.5 J of energy can be gathered in a 30 minute period through a copper plate.

In the article entitled ''Far-field RF wireless power transfer with blind adaptive beamforming for Internet of Things devices,'' Yedavalli et al., propose a wireless power transfer method for IoT devices using the concept of radio frequency beamforming in the radiative far field. In fact, a blind adaptive beamforming algorithm has been proposed for wireless power transfer for the IoT devices. The proposed algorithm is computationally light as it does not rely on channel state information. Authors validated the proposed algorithm using a test bed composed of multiple antennas based on software defined radio. They showed that the harvested power is increased with beamforming and that the gain can be increased by increasing the number of antennas.

Wireless sensor networks (WSNs) are composed of tiny battery operated wireless sensor devices [item 9) in the Appendix]. When the sensor devices use solar energy, a question arises as to how much energy will be available in the future depending on weather conditions. In the article entitled ''A new energy prediction algorithm for energy-harvesting wireless sensor networks with Q-learning'' by Selahattin Kosunalp, the author proposed a Q-Learning based solar energy prediction algorithm for wireless sensor devices. One of the features of the proposed Q-Learning algorithm is that it does not only consider past weather conditions but it also accounts for current weather conditions in the solar energy prediction process.

In order to decrease the carbon footprint of WSNs, energy harvesting techniques have been proposed. In the article entitled ''Optimal power control in green wireless sensor networks with wireless energy harvesting, wake-up radio and transmission control'' by Mahapatra et al., authors propose a wake-up radio scheme, an error control scheme, and an energy harvesting scheme to decrease the carbon footprint of WSNs. More precisely, authors formulated a utility lifetime maximization problem using a distributed dual sub-gradient algorithm based on Lagrange Multiplier method to decrease the carbon footprint of WSNs.

In the article entitled ''Optimal recharging with practical considerations in wireless rechargeable sensor network'' by Rao et al., authors considered a WSN in which a mobile charging vehicle is responsible for scheduled charging of the WSN. Authors considered both the charging distance and the angle while recharging the sensor nodes. Furthermore, authors proved that the charging vehicle would travel the shortest distance i.e., Hamiltonian distance. Additionally, through the proposed scheme, the charging efficiency has been improved by two times.

In the article entitled ''Maximizing lifetime in wireless sensor network for structural health monitoring with and without energy harvesting'' by Mansourkiaie et al., authors considered a WSN for structural health monitoring application. Authors proposed an optimization framework to improve the network lifetime of WSNs. They proposed two heuristic routing algorithms by using integer non-linear programming to formulate the problem and used Branch and Bound space algorithm to solve it. Authors considered both cases i.e., with and without energy harvesting, while evaluating the proposed heuristics.

In the article entitled ''Outage analysis of wireless-powered relaying mimo systems with non-linear energy harvesters and imperfect CSI'' by Zhang et al., authors considered a wireless powered relay network having multiple-input multiple-output system. Both energy harvesting and information decoding mechanisms are performed simultaneously at the relay node. Authors investigated the outage performance by considering that imperfect channel state information is available at both the source and destination nodes.

In the article entitled ''Precoding design of mimo amplify-and-forward communication system with an energy harvesting relay and possibly imperfect CSI'' by Benkhelifa et al., authors considered simultaneous wireless information and power transfer (SWIPT) in a MIMO system. Authors considered both the ideal and practical schemes and explored the rate-stored energy (R-E) tradeoff region.

In the article entitled ''Energy-efficient power allocation in energy harvesting two-way AF relay systems'' by Zhang et al., authors considered two-way amplify and forward relay systems and addressed the issue of energy efficiency optimization by using energy harvesting. Authors used non-linear fractional programming and Karush-Kuhn-Tuchker conditions, and thus achieved a closed-form solution.

In the article entitled ''Joint downlink/uplink design for wireless powered networks with interference'' by Diamantoulakis et al., authors addressed the cascaded near-far problem. The cascaded near-far problem arises due to different path loss values and it degrades the users' performance in a wireless network. Authors considered TDMA and NOMA for the uplink communication and rely on SWIPT.

Network coding is a technique wherein packets are encoded and decoded at intermediate nodes to achieve a gain in throughput and capacity. The technique has been widely used to improve the performance of different wireless networks such as cognitive radio networks [item 7) in the Appendix] and vehicular ad hoc networks [item 8) in the Appendix]. Network coding has also been applied to wireless networks in conjunction with energy harvesting. In the article entitled ''Delay and energy tradeoff in energy harvesting multi-hop wireless networks with inter-session network coding and successive interference cancellation'' by Liu et al., authors propose a cross layer framework that jointly considers scheduling, routing, and network coding for multi-hop wireless networks.

In the article entitled ''Distributed user association in energy harvesting dense small cell networks: a mean-field multi-armed bandit approach'' by Maghsudi et al., authors propose an energy harvesting scheme based on game theory. Authors considered a mean-field multi-armed bandit game to solve the uplink user association problem for the ultra-dense small cell network.

In the article entitled ''SURE: A novel approach for self healing battery starved users using energy harvesting'' by Selim et al., authors propose a self-healing scheme for user equipment. In fact, authors propose an energy harvesting technique between the network operator and a battery starved user. The proposed scheme relies on radio frequency (RF) energy harvesting in which the network operator delivers energy to the users which require energy.

In the second to last article of this Special Section entitled ''Performance limits of online energy harvesting communications with noisy channel state information at the transmitter'' by Zenaidi et al., authors propose a Markov process that models the energy arrival process in a wireless network. Authors also studied the asymptotic behavior of the communication system while considering high and low recharge rate regimes.

The last article of this Special Section is entitled ''Capacity region of Gaussian multiple-access channels with energy harvesting and energy cooperation'' by Dong et al. In this article, authors considered K-user multiple access channels and derived the capacity region of this channel.

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APPENDIX
RELATED WORKS

1) F. Akhtar and M. H. Rehmani, "Energy harvesting for self-sustainable wireless body area networks," *IT Prof.*, vol. 19, no. 2, pp. 32–40, Mar./Apr. 2017.
2) F. Akhtar and M. H. Rehmani, "Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 769–784, May 2015.
3) M. K. Afzal, M. H. Rehmani, A. Pescape, S. W. Kim, and W. Ejaz, "IEEE access special section editorial: The new era of smart cities: Sensors, communication technologies, and applications," *IEEE Access*, vol. 5, pp. 27836–27840, 2017.
4) A. Rachedi, M. H. Rehmani, S. Cherkaoui, and J. J. P. C. Rodrigues, "IEEE access special section editorial: The plethora of research in Internet of Things (IoT)," *IEEE Access*, vol. 4, pp. 9575–9579, 2017.
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6) A. Ahmad, M. H. Rehmani, H. Tembine, O. Mohammed, and A. Jamalipour, "Optimization for emerging wireless networks: IoT, 5G and smart grid communication networks," *IEEE Access*, vol. 5, pp. 2096–2100, 2017.
7) A. Naeem, M. H. Rehmani, Y. Saleem, I. Rashid, and N. Crespi, "Network coding in cognitive radio networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1945–1973, 3rd Quart., 2017.
8) F. Jamil, A. Javaid, T. Umer, and M. H. Rehmani, "A comprehensive survey of network coding in vehicular ad-hoc networks," *Wireless Netw.*, vol. 23, no. 8, pp. 2395–2414, 2017.
9) A. Ahmad, S. Ahmad, M. H. Rehmani, and N. U. Hassan, "A survey on radio resource allocation in cognitive radio sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 888–917, 2nd Quart., 2015.

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