Future Networks With Wireless Power Transfer and Energy Harvesting

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Wireless communication using radio frequency (RF) radiation has been around for over 100 years and has shaped our society significantly over the past 40 years. However, wireless is not just about communications. For very short ranges, wireless power supply by inductive power transfer has become a reality through several commercial products and standards (Wireless Power Consortium, Power Matters Alliance, Alliance for Wireless Power, and Rezence). Far-field wireless power transfer (WPT) and wireless energy harvesting (WEH) via RF (as in wireless communications) on the other hand could be used for a longer range. Although it has long been seen as a potential for powering low-power devices, it is only recently that wireless (via RF) power has been recognized as a promising technology to cope with the explosion of low-power devices in future networks. Driven by the reduction in the energy needs of electronic devices (remember Koomey's law according to which, in 20 years, a device will require 10 000 times less energy to compute a given task) and the advent of trillions of internet device objects [Internet of Things (IoT)], there is a need to rethink the design of the network of the future so that wireless can reach its full potential not only to carry information but also to transfer energy.

> This month's special issue provides an overview of the state-of-the-art technology and theory for future networks with wireless power transfer and energy harvesting.

Recent research argues that the future of wireless networks will go beyond traditional communication-centric transmission. Just as wireless has disrupted wireless communications over the past 40 years, wireless will disrupt the delivery of wireless power. However, today's wireless networks are designed only for communication. Although wireless communication has become a relatively mature technology currently evolving toward the fifth generation, the development of wireless power is still in its infancy and has not even reached the first generation. There is no single standard for far-field WPT.

Wireless power will bring many new opportunities such as no wires, no contacts, no batteries, small form factor, genuine mobility and a perpetual, predictable, dedicated, on-demand, and reliable energy supply as opposed to ambient energy-harvesting technologies (solar, thermal, vibration). This is very relevant for future networks with ubiquitous and autonomous low-power devices,

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device-to-device communication, and the IoT with large-scale connectivity. It also prevents (or reduces) the massive disposal of batteries, which in turn preserves the environment and allows operation in hazardous or hard-to-reach environments (e.g., biomedical implants).

WPT has a long history. After Tesla's attempt in 1899, all WPT experiments in 1960–2000 were directed toward long-range, high-power transmission (such as solar-powered satellites and radio-powered airplanes). More recently, WPT and WEH have generated considerable interest to deliver relatively low power (e.g., μW to several W) over moderate distances (e.g., several m to several hundred m) due to the need to establish a reliable and convenient wireless power system to remotely charge various low- to medium-power devices such as RFID tags, sensors, and consumer electronics.

In addition, while radio waves simultaneously carry energy and information, the transmission of these quantities has traditionally been treated and studied separately. This further isolated the wireless power engineer from the wireless communication engineer. Instead, imagine a wireless network, e.g., WiFi or beyond 5G, where information and energy flow together over a wireless medium. Wireless communications, or wireless information transfer (WIT) and WPT, represent two extreme strategies, targeting communications only and power supply, respectively. On the other hand, the integrated design of wireless information and power transmission (WIPT) has the ability to evolve smoothly between these two extremes to make the best use of the RF spectrum/radiation and the network infrastructure to communicate and energize.

The design of wireless power systems and the integration of wireless power and wireless communication present new challenges and opportunities and require a paradigm shift in the design of wireless networks. As a result, in recent years, numerous new research problems and challenges have appeared that cover a wide range of disciplines such as power electronics, microwave theory and technology, RF and antenna design, communication theory, information theory, circuit theory, signal processing, protocol design, optimization, prototyping, and experimentation. Interest in wireless power and the interplay between wireless power and wireless communications has also spurred new directions of research and new tools in communities that do not traditionally work on wireless power, such as communications and signal processing engineers.

This special issue reflects the recent developments and extensive research conducted in the past decade across various communities in the area of WPT, WEH, and WIPT. This is the first special issue in Proceedings of the IEEE dedicated entirely to this unique topic. This issue not only complements but also contrasts with the Proceedings of the IEEE's June 2013 special issue on WPT, where the focus was on power electronics, antenna, and RF designs exclusively, without the consideration for communications, signal and system design, and the convergence between wireless power and wireless communications. The topic of near field and far-field WPT has traditionally been explored in the IEEE Power Electronics, the IEEE Microwave Theory and Techniques, and the IEEE Antennas and Propagation societies, in journals such as IEEE Transactions on Power Electronics, IEEE Transactions on Microwave Theory and Techniques, and IEEE Transactions on Antennas and Propagation. More recently, since 2013, the topic of communications and signal design for WPT and more generally wireless information and power transfer has emerged as a new and significantly growing research area in the IEEE Communications, IEEE Signal Processing, IEEE Information Theory, and IEEE Vehicular Technology societies, and IEEE Sensor Council, and in journals such as IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, IEEE Transactions on Signal Processing, IEEE Transactions on Vehicular Technology, IEEE Transactions on Information Theory, IEEE Journal on Selected Areas in Communications, IEEE Journal of Selected Topics in Signal Processing, and IEEE Internet of Things Journal. This special issue aims at capitalizing on the recent advances made in all those societies in the general area of wireless power. In contrast to 2013 where much emphasis was put on near-field WPT, the quasi totality of this special issue focuses on the emerging far-field WPT and WIPT.

Two special issues on wireless transmission of information and power were recently published in IEEE Journal on Selected Areas in Communications in January 2019 and February 2019, and in IEEE Journal of Selected Topics in Signal Processing in August 2021. Those special issues were aimed at authors from the communication and signal processing societies, and no papers were covering the electronics, antenna, and RF designs aspects of WPT and WIPT. In this special issue, on the other hand, the emphasis is on bridging a wide range of communities working on WPT and WIPT, such as IEEE Power Electronics, IEEE Microwave Theory and Techniques, IEEE Circuit and Systems, IEEE Antennas and Propagation, IEEE Communications, IEEE Signal Processing, IEEE Information Theory, and IEEE Vehicular Technology societies.

I. OVERVIEW OF THE SPECIAL ISSUE

The objective of this special issue is to demonstrate the significant benefits and applications of WPT and WEH in future networks. It focuses on various theoretical and practical design issues of WPT and energy harvesting, and on the integration of wireless communications and wireless power. The aim is to bring together researchers working in the related areas to share their views on major challenges, recent advances and future trends. Through ten invited papers, this special issue provides an overview of the state-of-the-art technology and theory for future networks with WPT and energy harvesting and covers a wide range of topics spanning RF and microwave design, antennas, materials, integrated circuits, signal design and processing, communications, safety, security, and radio system prototyping.

Foundations of Wireless Information and Power Transfer: Theory, Prototypes, and Experiments
by B. Clerckx, J. Kim, K. W. Choi, and D. I. Kim
This article provides a tutorial overview of the fundamental theoretical building blocks of WPT and WIPT followed by a discussion on the state-of-the-art experimental setups and prototypes. Theoretical and experimental results are contrasted and the authors show how the integration of RF, signal, and system designs in WPT and WIPT lead to new theoretical and experimental design challenges for both microwave and communication engineers. Promising solutions and avenues for future research are also discussed.

Metamaterials and Metasurfaces for Wireless Power Transfer and Energy Harvesting
by J. Zhou, P. Zhang, J. Han, L. Li, and Y. Huang
In this review article, it is shown that metamaterials and metasurfaces can significantly improve the power transfer efficiency and operational distance for WPT systems. Several different metamaterial approaches are reviewed, including 1) making reception less sensitive to incident wave angle and polarization; 2) achieving a higher RF to dc conversion efficiency; and 3) using them as parasitic elements or loading components to improve WEH performance in terms of circuit size, beamwidth, and conversion efficiency. Future opportunities for metamaterials and metasurfaces are also discussed.

Far-Field Wireless Power Harvesting: Nonlinear Modeling, Rectenna Design, and Emerging Applications
by X. Gu, S. Hemour, and K. Wu
In this review article, recent developments and technology trends in far-field (radiative) wireless power harvesting are presented, including modeling of the rectification process, insights into the integration of the rectifier and antenna (rectenna), and demonstrations of emerging applications. The nonlinear semiconductor device behavior is explored, with the goal to provide a guideline for easy device selection. Rectenna design is discussed, with a focus on efficiency at low power levels.

Broadband RF Energy-Harvesting Arrays
by E. Kwiatkowski, J. A. Estrada, A. López-Yela, and Z. Popović
This article compares design methodology and scalability of narrowband and broadband rectenna arrays for RF energy harvesting. An example 10-GHz narrowband rectifier array is presented for ultralow-power ground-based harvesting of narrowband satellite signals. This is contrasted to harvesting over a greater than octave bandwidth, through a comparison of several broadband rectenna arrays for harvesting multiple widely spaced simultaneous signals.

Adaptive Wireless Power Transfer and Backscatter Communication for Perpetual Operation of Wireless Brain–Computer Interfaces
by G. E. Moore, J. D. Rosenthal, J. R. Smith, and M. S. Reynolds
This article describes efforts in eliminating tethers in brain–computer interfaces (BCIs) used in fundamental neurophysiology research. The two approaches detailed in the article are ultralow-power wireless backscatter communication and adaptive inductive resonant (AIR) WPT toward fully wireless BCIs having wireless uplink of broadband neural recordings and wireless recharging for long-duration deployment.

Design and Analysis of SWIPT With Safety Constraints
by C. Psomas, M. You, K. Liang, G. Zheng, and I. Krikidis
This article focuses on the design of WIPT subject to health and safety constraints. A framework for the design, analysis and optimization under specific absorption rate (SAR) and maximum permissible exposure (MPE) is formulated and insights are derived.

Resource Allocation for Simultaneous Wireless Information and Power Transfer Systems: A Tutorial Overview
by Z. Wei, X. Yu, D. W. K. Ng, and R. Schober
This article focuses on the resource allocation problem in multiuser WIPT with various models for the energy harvester and the channel state information. A resource allocation optimization framework is formulated to characterize the rate-energy tradeoff and draw insights into the system design. Future research directions are also discussed.

Intelligent Reflecting Surface-Aided Wireless Energy and Information Transmission: An Overview
by Q. Wu, X. Guan, and R. Zhang
This article provides an overview of WPT and WIPT aided by intelligent reflecting surfaces (IRSs) from a communication and signal processing perspective. State-of-the-art solutions to tackle the unique challenges in operating these systems are presented and include IRS passive reflection optimization, channel estimation and deployment. Important directions for future research and investigation are also discussed.

Advances in Wirelessly Powered Backscatter Communications: From Antenna/RF Circuitry Design to Printed Flexible Electronics
by C. Song, Y. Ding, A. Eid, J. G. D. Hester, X. He, R. Bahr, A. Georgiadis, G. Goussetis, and M. M. Tentzeris
This article focuses on the use of backscatter communications in WPT systems. Specific areas highlighted include newly emerged rectenna

systems, waveform design and channel optimization, advanced device packaging and integration technologies and also inkjet printing for sustainable systems. Future directions of backscatter communication in terms of "Green IoT" and "Low Carbon" smart home, smart city, smart skin, and machine-to-machine (M2M) applications are also discussed.

Secure Wirelessly Powered Networks at the Physical Layer: Challenges, Countermeasures, and Road Ahead
by X. Lu, N. C. Luong, D. T. Hoang, D. Niyato, Y. Xiao, and P. Wang
Providing security using low-power physical layer techniques is discussed in this article. The article reviews fundamental principles of primary PHY attacks, covering jamming, eavesdropping, and detection of covert. It then describes prevalent countermeasures to secure both active and passive communications in WPNs. Open research issues are also identified to inspire possible future research. ■

ABOUT THE GUEST EDITORS

Bruno Clerckx (Fellow, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from the Université Catholique de Louvain, Louvain-la-Neuve, Belgium, in 2000 and 2005, respectively.

From 2006 to 2011, he was with Samsung Electronics, Suwon, South Korea, where he actively contributed to 4G (3GPP LTE/LTE-A and IEEE 802.16m) and acted as the Rapporteur for the 3GPP Coordinated Multi-Point (CoMP) Study Item. Since 2011, he has been with Imperial College London, London, U.K., first as a Lecturer from 2011 to 2015, a Senior Lecturer from 2015 to 2017, a Reader from 2017 to 2020, and currently as a Full Professor. From 2014 to 2016, he was an Associate Professor with Korea University, Seoul, South Korea, and from 2021 to 2022, he is a Visiting Professor at Seoul National University, Seoul. He has also held various long or short-term visiting research appointments at Stanford University, Stanford, CA, USA; EURECOM, France; National University of Singapore, Singapore; The University of Hong Kong, Hong Kong; Princeton University, Princeton, NJ, USA; The University of Edinburgh, Edinburgh, U.K.; The University of New South Wales, Sydney, NSW, Australia; and Tsinghua University, Beijing, China. He is a (Full) Professor, the Head of the Wireless Communications and Signal Processing Laboratory, and the Deputy Head of the Communications and Signal Processing Group, Electrical and Electronic Engineering Department, Imperial College London. He has authored two books on multiple input–multiple output (MIMO) wireless communications and MIMO wireless networks, 250 peer-reviewed international research articles, and 150 standards contributions, and is the inventor of 80 issued or pending patents among which 15 have been adopted in the specifications of 4G standards and are used by billions of devices worldwide. His research spans the general area of wireless communications and signal processing for wireless networks.

Dr. Clerckx has been a Technical Program Committee (TPC) Member, a Symposium Chair, or a TPC Chair of many symposia on communication theory, signal processing for communication, and wireless communication for several leading international IEEE conferences. He was an Elected Member of the IEEE Signal Processing Society "Signal Processing for Communications and Networking" (SPCOM) Technical Committee. He received the prestigious Blondel Medal 2021 for exceptional work contributing to the progress of Science and Electrical and Electronic Industries. He served as an Editor for IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, and IEEE TRANSACTIONS ON SIGNAL PROCESSING. He has also been a (Lead) Guest Editor for special issues of the *EURASIP Journal on Wireless Communications and Networking*, IEEE Access, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING, and PROCEEDINGS OF THE IEEE. He was an Editor of the 3GPP LTE-Advanced Standard Technical Report on CoMP. He is an IEEE Communications Society Distinguished Lecturer from 2021 to 2022.

Zoya Popović (Fellow, IEEE) received the Dipl.Ing. degree from the University of Belgrade, Belgrade, Serbia, in 1985, and the Ph.D. degree from the California Institute of Technology, Pasadena, CA, USA, in 1990.

She was a Visiting Professor with the Technical University of Munich, Munich, Germany, from 2001 to 2003, and with the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), Toulouse, France, in 2014. She was the Chair of Excellence with the Carlos III University of Madrid, Madrid, Spain, from 2018 to 2019. She is a Distinguished Professor and the Lockheed Martin Endowed Chair of Radio Frequency (RF) Engineering at the University of Colorado at Boulder, Boulder, CO, USA. She has graduated over 65 Ph.D. students and currently advises 18 doctoral students. Her current research interests include high-efficiency power amplifiers and transmitters, microwave and millimeter-wave high-performance circuits for communications and radar, wireless powering, medical and industrial applications of microwaves, and microwave techniques applied to quantum sensing and metrology.

Dr. Popović was a recipient of two IEEE Microwave Theory and Technique Society (MTT-S) Microwave Prizes for best journal papers, the White House National Science Foundation (NSF) Presidential Faculty Fellow Award, the American Association for Engineering Education/Hewlett Packard (ASEE/HP) Terman Medal, and the German Humboldt Research Award. She was the first woman to win the International Union of Radio Science (URSI) Issac Koga Gold Medal in 1993 and was named the IEEE MTT Distinguished Educator in 2013 and the University of Colorado Distinguished Research Lecturer in 2015. She was elected as a Foreign Member of the Serbian Academy of Sciences and Arts in 2006. She is passionate about increasing the number of excellent women engineers and scientists, with eight women Ph.D. students currently in her group.

Ross Murch (Fellow, IEEE) received the B.E. and Ph.D. degrees in electrical and electronic engineering from the University of Canterbury, Christchurch, New Zealand.

He was the Department Head at the Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology (HKUST), Hong Kong, for two 3-year terms from 2009 to 2015. He was also the founding Director of the Center for Wireless Information Technology and acts as a consultant for industry and government. He has been a David Bensted Fellow of Simon Fraser University, Burnaby, BC, Canada, an Hong Kong Telecom Institute of Information Technology (HKTIIT) Fellow at Southampton University, Southampton, U.K., and has spent sabbaticals at Massachusetts Institute of Technology, Cambridge, MA, USA; AT&T, Newman springs, USA; Allgon Mobile Communications, Åkersberga, Sweden; Imperial College London, London, U.K. He is a Chair Professor with the Department of Electronic and Computer Engineering and an Institute of Advanced Study (IAS) Senior Fellow of the Institute of Advanced Study at HKUST. He has a strong interest in education, enjoys teaching, and has won three teaching awards. In 1992, he joined HKUST as an Assistant Professor, where he is currently a Chair Professor. From 1990 to 1992, he was a Postdoctoral Fellow at the Department of Mathematics and Computer Science, University of Dundee, Dundee, U.K. His research contributions include more than 300 publications and 20 patents as well as successfully supervising more than 50 research students. His unique expertise lies in his combination of knowledge from both wireless communication systems and electromagnetic areas. He is the only author worldwide with more than 25 journal articles in each of IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. His current research interests include Internet-of-Things, radio frequency (RF) imaging, ambient RF systems, energy harvesting, multiport antenna systems, and reconfigurable intelligent surfaces.

Dr. Murch is a Fellow of the Institute of Engineering Technology (IET) and the Hong Kong Institution of Engineers (HKIE) and has won several awards, including the Computer Simulation Technology (CST) University Publication Award in 2015. He was a Distinguished Invited Speaker at the Wireless Communication and Networking Conference (WCNC) 2016 and a Keynote Speaker at IEEE International Conference on Communication Technology (ICCT) 2011, IEEE Asia–Pacific Wireless Conference (APWC) 2008, IEEE Gulf Cooperation Council (GCC) 2007, and IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM) 2007. He was also a Chair of the IEEE Communications Society's Technical Committee on Wireless Communications, a member of the IEEE Communications Society Fellow Evaluation Committee, and a member of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS's Steering Committee. He has also been the Publication Editor, Area Editor, and Associate Editor of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and was also a Distinguished Lecturer of the IEEE Vehicular Technology Society. He has also been the Technical Program Chair of the IEEE Wireless Communications and Networking Conferences in 2019 and 2007, the Keynote Chair of the IEEE International Conference on Communications in 2010, and the Technical Program Chair of the Advanced Wireless Communications Systems Symposium in IEEE International Communications Conference in 2002.