Wireless Power Transmission, Technology, and Applications

By KE WU, *Fellow, IEEE*
Guest Editor

DEBABANI CHOUDHURY, *Fellow, IEEE*
Guest Editor

HIROSHI MATSUMOTO, *Fellow, IEEE*
Guest Editor

Radio-frequency (RF)-based wireless technology enables three different basic system functions, namely, wireless communication (data/voice), wireless sensing (parameter), and wireless powering (energy). The first two well-known wireless applications have been found today in nearly all social and economic activities, which have been transforming our daily life. However, the wireless power transmission or transfer (WPT), which is less known at least publicly, has not yet been well developed and established as one of the fundamental driving forces for wireless applications. Strictly speaking, any natural or man-made electromagnetic radiation and transmission in space should be called WPT, including today's popular solar power harvest systems because sunlight is just a set of mixed electromagnetic spectra. We often refer to the WPT for the use of "electrical-oriented" power transmission purposes at RFs that are much lower than their infrared and optical counterparts. Infrared and optical frequencies present some challenge for WPT under severe weather conditions such as foggy and rainy days.

This special issue focuses on the historical development, state-of-the-art, and future outlook of wireless power technology, transmission, and applications.

The idea of WPT is not new at all; it was first considered more than a century ago by Nikola Tesla (U.S. Patent 685 954, November 1901). His experiment was not successful even though he attempted to demonstrate its feasibility. This failure was caused by the lack of certain radio-wave technologies at that time. With a series of technological attempts and historical demonstrations, the wireless power has finally come out of age. Currently, four major technological factors have been driving the research progress of various wireless power transmission and technologies for about two decades, namely high-density power devices, low-power integrated circuits (ICs), high-efficiency rectennas, and innovative circuit architectures. In addition, emerging applications and markets have been playing critical roles in the promotion and "push-forward" of WPT such as the power harvest of battery-free implanted complementary metal–oxide–semiconductor (CMOS) devices for biomedical engineering, contactless radio-frequency identification (RFID) for security applications and transportations, and remote charging and powering of electronic vehicles and mobile devices.

This special issue focuses on the historical development, state of the art, and future outlook of wireless power technology, transmission, and applications. A wide range of topics are covered within 18 papers selected for this issue, which fall into in the following three categories: 1) proximity (near-contact) and near-field power delivery through electrical and/or magnetic inductions; 2) short-range

Digital Object Identifier: 10.1109/JPROC.2013.2257590

and midrange wireless power transfer through coupled resonant circuits; and 3) long-haul wireless power transmission through RF rectifying circuits. In addition, the research and development progress and prospects of solar power satellite (SPS) technologies and systems for microwave WPT are presented. Safety concerns and interference assessment are also discussed with respect to WPT.

As revealed by this special issue, WPT and its related technology development have recently generated significant interest and applications around the world. Some startup or small-size companies have exploited market-oriented WPT applications. A number of medium and large-size corporations have invested significant R&D manpower and budgets into the development of their product-oriented special WPT technologies. The SPS technology opens up the possibility of constructing power stations in space and/or on the moon, which will be capable of transmitting power to Earth using microwave energy beams. The transmitted microwave energy could then be captured and converted into electricity using a large array of rectenna receivers on Earth.

Obviously, WPT could revolutionize our energy sector, our information and communication technology (ICT) sector, our environment sector, and our medical sector. First, the proposed SPS would bring clean energy from natural sunlight in space to power Earth without using the resources of our planet. This could fundamentally change the landscape of resource planning and energy renewable strategies. Numerous existing devices and circuits technologies can directly be used or recycled into the WPT research and development.

Although a large number of research and development activities related to WPT are currently going on and a growing list of applications is envisaged for immediate and future use, there is a lack of concentrated state-of-the-art information on this very important topic. In fact, most of the WPT research publications have been widely scattered in various journals and magazines, starting from publications like *Science* to *Industrial News Reports*. In fact, WPT involves a very wide range of research and development topics such as device technology, system architecture, antenna systems, material engineering, transmission safety, interference issue, application development, and market economy. It is rather difficult for us to consider all those aspects in a single technical journal or magazine. But, this special issue attempts to fulfil the void for our community to develop a topical "overview," present the current results, and also share our collective "vision" for the future. We are thankful for the enthusiastic contributions from various research groups in academia, industries, research institutions, and government agencies around the world. The collective contributions provided an opportunity to create an archival reference for furthering and expanding R&D activities in the field.

As guest editors, we have done our utmost to reduce the overlap of technical contents among the selected papers in the special issue. But in papers of closely related subjects some overlap is unavoidable during the actual presentations and discussions. Our goal is to cover the widest possible range of related topics, but we have excluded infrared and optical power harvest techniques, as we present WPT techniques defined in the electrical and RF spectrum.

To make the presentation logical and sequential, we organized the articles in groups based on work frequency, power level, wireless range, and operating technique. The special issue begins with the first group of three papers that address the proximity power transfer issues with induction techniques based on the kilohertz-frequency range for relatively high power applications. Following a general presentation on various near- and far-field issues and deployments by the two subsequent papers, the second group of four papers examines different techniques on coupled resonance technologies operating over the megahertz range, even though a possible extension into gigahertz is also addressed. Such coupled resonance techniques are based on near-field scenarios for delivering midlevel power. The third group of seven papers focuses on the rectenna-based long-range WPT techniques including SPS and discusses fundamental issues, technological advancements, and potential applications. Compared to the induction- and coupled-resonance-based WPT, which have been capitalized by industry through industrial standards and forums, the long-range wireless powering is still subject to academic research, and has not been well exploited yet by the end users and industry. This is because there are a number of challenging problems such as wireless power level and dynamic efficiency issues. The last group of two papers is concerned with human exposure and EMC- and EMI-related problems with respect to electromagnetic fields through WPT, which is important and cannot be ignored for large-scaled commercial applications of WPT.

The first paper, "Inductive power transfer" by Covic and Boys, details the historical background, technological issues, and engineering applications of inductive power transfer. A comprehensive analysis on the functions of inductive power transfer is given. The authors share their vision and arguments on the engineering challenges and future developments such as roadway powered systems.

The second paper, "Planar wireless charging technology for portable electronic products and Qi" by Hui, begins with the importance of wireless power charging and its historical roots. The author then discusses recent system platforms based on planar charging as well as its critical issues and related technologies. The information on the first wireless power standard "Qi" is then presented with future trends and development predictions in this field with examples.

The third paper, "An overview of technical challenges and advances of inductive wireless power transmission" by Mayordomo *et al.*, emphasizes the technical issues in connection with design parameters. The authors briefly discuss the principle of inductive coupling and then present a number of related applications. Subsequently, WPT-based projects, mainly developed in Germany, are presented to highlight the importance of inductive WPT.

In the fourth paper, "Issues and initiatives for practical deployment of wireless power transfer technologies in Japan" by Shoki, various WPT-related social/political issues, technical problems, and commercial applications in Japan are addressed. Three basic WPT techniques are briefly discussed in connection with tradeoff and usage models as well as practical problems. The author highlights Japanese activities with focus on the development of WPT regulations. WPT-related standards and industrial consortia in Japan are also presented.

The fifth paper, "Wireless power transmission: From far field to near field" by Garnica *et al.*, addresses the historical issues of WPT and then examines techniques and applications from far-field to near-field WPT platforms. The authors review technological advances in the short-range and midrange near-field systems with a series of examples and results. They point out the advantages of near-field WPT for practical applications.

The sixth paper, "Coil design and shielding methods for a magnetic resonant wireless power transfer system" by Kim *et al.*, starts with the presentation of basic principle of WPT based on magnetic field resonance with parametric effects. The authors look into the electromagnetic field noise from WPT and related shielding and cancellation methodologies. Different application scenarios are described with design considerations.

The seventh paper, "Enabling seamless wireless power delivery in dynamic environments" by Sample *et al.*, reviews magnetically coupled resonance techniques and related challenging problems. In particular, this paper discusses various methods used to adapt to the variations in range, orientation, and load, using both wideband and fixed-frequency techniques. A dynamically adaptive system is demonstrated with optimal efficiency.

Also with the platform of coupled resonance technique, the eighth paper, "Wireless power transfer: Metamaterials and array of coupled resonators" by Wang *et al.*, reports the use of metamaterials in the WPT design. With theoretical and experimental validations, it is shown that the power transfer efficiency and coupling can be enhanced by this scheme as well as the use of arrayed resonators can extend the range. With a particular interest of WPT in implantable systems, the ninth paper, "Midfield wireless powering for implantable systems" by Ho *et al.*, presents special advantages of high-efficiency midfield wireless powering when the source and the receiver are weakly coupled. An overview of different implants is provided and theoretical investigations are carried out to model the behavior of midfield power transfer systems.

The tenth paper, "Microwave power transmission: Historical milestones and system components" by Strassner and Chang, presents a comprehensive overview of the key historical developments of microwave power transmission (MPT) in chronological detail, covering space solar power (SSP) and SPS background, rectenna invention as well as WPT experiments and demonstrations in many countries. Key components and design techniques are discussed to achieve high-efficiency MPT with special emphasis on long-range rectenna-based system developments, which are supported by many examples.

The following two papers review and discuss the long-range far-field wireless power harvesting through low ambient power sources and specially dedicated RF and microwave sources. Immediate applications of this low-power can be found in powering wireless sensors. In the eleventh paper, "Low-power far-field wireless powering for wireless sensors" by Popovic *et al.*, the far-field powering issues are addressed for low-power and low-duty cycle wireless sensors with low incident power density. It is found that the codesign of wireless powering and power management modules should be made to achieve optimal efficiency. Various technical details and design examples are examined in connection with low-power rectenna and power management system. Similarly, the twelfth paper, "RF energy harvesting and transport for wireless sensor network applications: Principles and requirements" by Visser and Vullers, reviews the principles and technical aspects of RF energy harvesting or transport (delivery) for powering wireless sensors. Application-oriented discussions are provided with development considerations. Design issues and technical details of RF harvesters are also examined with some examples of applications in the end.

The next two papers review the development of SSP and address various technical aspects and provide an outlook into the future of this large-scaled project. The thirteenth paper, "Energy conversion and transmission modules for space solar power" by Jaffe and McSpadden, reviews an exhaustive and historical background of SSP developments in connection with U.S. Department of Energy (DOE)/National Aeronautics and Space Administration (NASA) projects. Basic concepts of MPT used for SSP transmission and conversion as well as technical parameters and enabling technologies are discussed, such as beaming control and sandwich module. Recent advances and efforts have been also detailed. On the other hand, the fourteenth paper, "Microwave power transmission technologies for solar power satellites" by Sasaki *et al.*, looks into the concept and historical background of SPS and discusses various technological issues and other aspects for such SPS applications in connection with MPT. The authors present the past demonstrations of SPS and discuss also a recent Japanese project that involves a number of technical parameters and design considerations. A technology roadmap is revealed to highlight the R&D directions of SPS.

Arrayed transmitting power stations and receiving rectenna systems are generally used for high-power wireless delivery, which are examined by the following two papers. The fifteenth paper, "Beam control technologies with a high efficiency phased array for microwave power transmission in Japan" by Shinohara, summarizes the past and recent Japanese efforts in the development of MPT. Particular interest is placed on phased array technologies for MPT developments with reference to the past and current projects. A wealth of examples is shown with both solid-state- and magnetron-based power technologies. In the sixteenth paper, "Array designs for long-distance wireless power transmission: State-of-the-art and innovative solutions" by Massa *et al.*, a number of long-range WPT array design issues are covered with theoretical formulations and analyses. A review of those array techniques is provided with recent advances and future trends. Design techniques for transmitting antennas are developed for optimized array architectures. Synthesis issues of rectenna arrays are detailed with examples and discussions.

The last two papers focus on the pressing issues of electromagnetic safety and security when it comes to the practical applications of WPT or wireless power systems (WPSs). The seventeenth paper, "Assessing human exposure to electromagnetic fields from wireless power transmission systems" by Christ *et al.*, reviews the safety guidelines, standards such as SAR, and interactions between human body and near fields. Then, the authors present various models, numerical methods, and experimental techniques for assessing the risk issues of human exposure to electromagnetic fields (EMFs). The evaluation of an application case suggests that more long-term studies are required. In particular, a number of open issues are raised, which must be addressed in the community. With the biological effects of EMF in mind, the last (eighteenth) paper, "Cellular and molecular responses to radio-frequency electromagnetic fields" by Miyakoshi, examines the human exposure to nonionized EMF in connection with WPT applications. The author discusses results of recent cellular studies on RF EMF effects and their physiological impacts from alternative viewpoints of life sciences with references to the common perception and general knowledge of electrical engineers about EMF safety. Various biological and biomedical aspects are highlighted in connection with DNA, mutation, cell, gene, and others.

The WPT, wireless power harvesting techniques, and applications are generating huge renewed R&D interests in both academia and the industry. The current efforts can be seen in three directions. One is to further develop the near-field-based wireless power transfer techniques for larger coverage, better efficiency, and higher power, and also to standardize the coupled resonance WPT. The second direction is to exploit high-power SPS or SSP-related techniques for massive wireless power transfer. The third direction is to investigate low-power and high-efficiency wireless power harvesting techniques for recycling the weak ambient electromagnetic sources, which requires innovative rectenna schemes and high-efficient radio-frequency to direct current (RF-to-dc) power conversion even if the incident RF power is low, usually at microwatts level. We hope that this special issue will serve as a fundamental reference source for researchers and practitioners in the field for many years to come. ■

Acknowledgment

The guest editors are grateful to the authors of all the submitted papers for their contributions to this special issue, to the reviewers for their constructive comments and suggestions, and to R. Trew, the former Editor-in Chief, J. Calder, the former Managing Editor, and J. Sun and M. Meyer, the Publications Editors, for their professional support throughout the preparation of this special issue. The guest editors would also like to acknowledge the contributions of Dr. S. Hemour of the Ecole Polytechnique de Montreal, Montreal, QC, Canada, and Dr. N. Shinohara of Kyoto University, Kyoto, Japan, for their assistance during the development of this special issue.

ABOUT THE GUEST EDITORS

Ke Wu (Fellow, IEEE) received the B.Sc. degree (with distinction) in radio engineering from Nanjing Institute of Technology (now Southeast University), Nanjing, Jiangsu, China, in 1982 and the D.E.A. and Ph.D. degrees in optics, optoelectronics, and microwave engineering (with distinction) from Institut National Polytechnique de Grenoble (INPG) and University of Grenoble, Grenoble, France, in 1984 and 1987, respectively.

He is a Professor of Electrical Engineering, and Tier-I Canada Research Chair in RF and Millimeter-Wave Engineering at the Ecole Polytechnique (University of Montreal), Montreal, QC, Canada. He holds the first Cheung Kong endowed chair professorship (visiting) at Southeast University, the first Sir Yue-Kong Pao chair professorship (visiting) at Ningbo University, and an honorary professorship at the Nanjing University of Science and Technology, the Nanjing University of Post Telecommunication, and the City University of Hong Kong, China. He has been the Director of the Poly-Grames Research Center and the founding Director of the Center for Radiofrequency Electronics Research of Quebec (Regroupement stratégique of FRQNT). He has also held guest and visiting professorship at many universities around the world. He has authored or coauthored over 900 refereed papers, and a number of books/book chapters and filed more than 30 patents. His current research interests involve substrate integrated circuits (SICs), antenna arrays, advanced computer-aided design (CAD) and modeling techniques, wireless power transmission and harvesting, and development of low-cost RF and millimeter-wave transceivers and sensors for wireless systems and biomedical applications. He is also interested in the modeling and design of microwave photonic circuits and systems.

Dr. Wu is a member of the Electromagnetics Academy, the Sigma Xi Honorary Society, and the International Union of Radio Science (URSI). He has held key positions in and has served on various panels and international committees including the chair of technical program committees, international steering committees, and international conferences/symposia. In particular, he was the General Chair of the 2012 IEEE MTT-S International Microwave Symposium. He has served on the editorial/review boards of many technical journals, transactions, proceedings, and letters, as well as scientific encyclopedia including editors and guest editors. He is currently the chair of the joint IEEE chapters of MTTS/APS/LEOS in Montreal. He is an elected IEEE MTT-S AdCom member for 2006–2015 and served as Chair of the IEEE MTT-S Transnational Committee and Member and Geographic Activities (MGA) Committee among many other AdCom functions. He was the recipient of many awards and prizes including the first IEEE MTT-S Outstanding Young Engineer Award, the 2004 Fessenden Medal of the IEEE Canada, the 2009 Thomas W. Eadie Medal of the Royal Society of Canada, and the Queen Elizabeth II Diamond Jubilee Medal. He is a Fellow of the Canadian Academy of Engineering (CAE) and a Fellow of the Royal Society of Canada (The Canadian Academy of the Sciences and Humanities). He was an IEEE MTT-S Distinguished Microwave Lecturer from January 2009 to December 2011.

Debabani Choudhury (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the Indian Institute of Technology, Bombay (IITB), India, in 1991.

She has broad range of expertise in RF, millimeter wave, and terahertz circuits, system and technologies. Currently, she is a Senior Technologist at Intel Labs, Portland, OR, USA, and performs research on RF technologies for small-form factor wireless platform integration. Before joining Intel in 2006, she held senior research staff positions at HRL Labs (formerly Hughes Research Laboratories) and Millitech Corporation where she developed various millimeter-wave and terahertz technologies for imaging and other space and defense applications. Prior to that, she worked at NASA Jet Propulsion Laboratory (JPL) on submillimeter wave devices and components for space-based heterodyne receiver applications. She developed first dual-polarized beam steering arrays at 94 GHz for imaging applications. Her work on multigigabit package and wideband active amplifier development holds records. She also coinvented and developed state-of-the-art RF microelectromechanical (MEM) switches, tunable devices, and transceiver elements for millimeter-wave integrated circuit (IC) integration with ultralow-loss, harmonic-free switching, and tuning. She has more than 35 patents/patent applications and numerous publications.

Dr. Choudhury received several NASA recognition awards for her work on heterodyne receivers, devices, multipliers, and guiding structures/modules developed for space and defense applications. She has been on several Technical Program Committees (TPC) for IEEE and SPIE conferences including IEEE International Microwave Symposium (IMS), IEEE Antenna and Propagation Symposium (AP-S), IEEE Radio and Wireless Symposium (RWS), and Asia Pacific Microwave Conference (APMC). She is a member of multiple IEEE Microwave Theory and Technique Society (MTT-S) Technical Co-Ordination Committees: MTT-6 on Microwave and Millimeter Wave Integrated Circuits; MTT-20 on Wireless Communications; MTT-26 on Wireless Energy Transfer and Conversion. She has been elected as Vice-Chair of MTT-20: Wireless Communications Committee. She served on many IMS and RWS conference steering committee roles, including Publications Chair for several IEEE MTT-S conferences and TPC Co-Chair for 2013 IEEE RWS conference. She was the Guest Editor for multiple RWW special issues of the IEEE Microwave Magazine. She has presented numerous invited talks at various conferences, workshops, industries, and universities worldwide. She has presented and organized numerous IEEE workshops, panel sessions, and focused sessions. She is an IEEE Fellow for her contributions to millimeter-wave enabling technologies.

Hiroshi Matsumoto (Fellow, IEEE) received the B.S. and M.S. degrees and the Ph.D. degree in engineering from Kyoto University, Kyoto, Japan, in 1965, 1967, and 1973, respectively.

He was appointed President of Kyoto University, in 2008, prior to which he served as the university's Executive Vice-President for research and finance. Following the completion of his Ph.D., he was employed as an Associate Professor in Kyoto University's Faculty of Engineering before being appointed as a Professor (1987–2000) and Director (1992–1998) of the university's Radio Atmospheric Science Center. He then went on to serve as a Professor (2000–2002) and Director (2002–2004) of the university's Radio Science Center for Space and Atmosphere. In 2005, he was appointed Executive Vice-President for research, finance, and information infrastructure, and in 2006, Executive Vice-President for research and finance, a position which he held until his current appointment as President. He has published 302 scientific papers in English in international journals and 134 scientific papers in Japanese, and has authored and contributed to several books in the fields of space plasma waves, computer simulations, satellite observations, laboratory plasma experiments, and microwave energy transmission for solar power satellite and terrestrial applications, among other subjects.

Dr. Matsumoto has received several awards and distinctions including the NASA Group Achievement Award (1998), the Russian Federation of Cosmonautics Gagarin Medal (2006), the URSI Gold Booker Medal (2008), Medal with Purple Ribbon of Japanese Government (2007), and the Hasegawa Nagata Award, SGEPSS of Japan (2008).