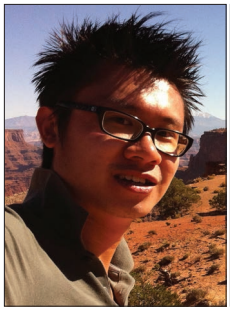
ENERGY HARVESTING COMMUNICATIONS: PART 1



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Over the last decade, energy harvesting has emerged as a promising approach to enable self-sufficient and self-sustaining operation for low-cost devices in energy-constrained networks by scavenging energy from the ambient environment to power up devices.

In wireless sensor networks, small, wireless, autonomous sensors usually operate at ultra-low power. If these wireless sensors, which spread throughout homes or factories, in buildings or even outdoors to monitor all kinds of environmental conditions, are powered by energy harvesting, there are no batteries to replace and no laborious cost associated with replacing them. As such, wireless sensor networks can be deployed in hard-to-reach areas to provide ubiquitous coverage.

In cellular networks, energy harvesting can be used to provide power in many elements of a telecom network, saving considerable cost in electricity supply and providing low maintenance monitoring. Powering base stations with wind or solar power allows telecom networks to expand beyond the limit of the power grid. The possibility of redistribution of the renewable energy in smart grid allows further efficient utilization, although it leads to many challenges as well.

Another important focus of this research area is RF energy harvesting. RF energy is currently broadcasted from billions of radio transmitters around the world, including mobile telephones, handheld radios, mobile base stations, and television/ radio broadcast stations. The ability to harvest RF energy, from ambient or dedicated sources, enables wireless charging of low-power devices and provides significant benefits to product design, usability, and reliability.

This Feature Topic includes 10 accepted papers, which address a number of critical and relevant issues studied in the emerging area of energy harvesting communications. We hope this Feature Topic is able to help readers obtain better understanding of some key issues in energy harvesting and drive more research interest.

This Feature Topic starts with an article, "Smart RF Energy Harvesting Communications: Challenges and Opportunities" by Deepak Mishra *et al.*, which explores various communication strategies that can complement the RF harvesting hardware advances toward the realization of energy harvesting communication networks.

The article "A General Utility Optimization Framework for Energy-Harvesting-Based Wireless Communications" by Hang Li *et al.* introduces a general utility optimization framework for energy-harvesting-based wireless communication systems subject to a novel type of energy usage constraint.

The article "Application of Smart Antenna Technologies in Simultaneous Wireless Information and Power Transfer," written by Zhiguo Ding *et al.*, proposes an application of smart antenna technologies, MIMO and relaying, to simultaneous wireless information and power transfer systems, and provides some future research challenges for the design of those systems.

The article "RF-Powered Cognitive Radio Networks: Technical Challenges and Limitations" by Lina Mohjazi *et al.* presents an overview of the architecture of cognitive radio networks that operate based on intended and unintended RF energy harvesting.

The article "Provisioning Quality of Service to Energy Harvesting Wireless Communications" by Xiaojing Chen *et al.* develops a dynamic string tautening method to produce the most energy-efficient schedule that adapts to the bursty characteristics of wireless traffic and energy harvesting.

The article "Increasing Sustainability and Resiliency of Cellular Networks Infrastructure by Harvesting Renewable Energy" by Andres Kwasinski *et al.* discusses the use of harvested renewable energy to power cellular base stations to reduce the carbon footprint of cellular infrastructure and to enable the deployment of cellular service in areas that lack electrification infrastructure.

The article "Wireless Powered Communication: Opportunities and Challenges," written by Suzhi Bi *et al.*, presents an overview of state-of-the-art RF enabled wireless energy transfer technology and it applications to wireless communications, with highlights on the key design challenges, solutions, and opportunities ahead.

The article "Fundamental Limits of Energy Harvesting

Communications" by Omur Ozel *et al.* surveys recent results in the literature and point to open problems in the fields of communication theory, information theory, signal processing, and networking.

The article "Enhancing Wireless Information and Power Transfer by Exploiting Multi-Antenna Techniques," written by Xiaoming Chen *et al.*, provides a tutorial on various aspects of multi-antenna-technique-based wireless information and power transfer, with a focus on tackling the challenges through parameter optimization and protocol design.

The article "Green Delivery: Proactive Content Caching and Push with Energy-Harvesting-Based Small Cells" by Sheng Zhou *et al.* proposes a new access network framework that enables efficient content delivery via energy-harvesting-based small cells to provide more multicast opportunities.

BIOGRAPHIES

CHAU YUEN (yuenchau@sutd.edu.sg) received his B. Eng and Ph.D. degrees from Nanyang Technological University, Singapore, in 2000 and 2004, respectively. He was a postdoctoral fellow at Lucent Technologies Bell Labs, Murray Hill, New Jersey, during 2005. He was a visiting assistant professor at Hong Kong Polytechnic University in 2008. During the period of 2006–2010, he worked at the Institute for Infocomm Research, Singapore, as a senior research engineer. He joined Singapore University of Technology and Design as an assistant professor in June 2010. He serves as an Associate Editor for *IEEE Transactions on Vehicular Technology* and was awarded Top Associate Editor for three consecutive years. In 2012, he received the IEEE Asia-Pacific Outstanding Young Researcher Award. He has held positions on several conference organizing committees, and is on Technical Program Committees of various international conferences.

MAGED ELKASHLAN received his Ph.D. degree in electrical engineering from the University of British Columbia, Canada, in 2006. From 2006 to 2007, he was with the Laboratory for Advanced Networking at the University of British Columbia. From 2007 to 2011, he was with the Wireless and Networking Technologies Laboratory at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. He also held an adjunct appointment at the University of Technology Sydney, Australia, between 2008 and 2011. In 2011, he joined the School of Electronic Engineering and Computer Science at Queen Mary, University of London, United Kingdom, as an assistant professor. His research interests include millimeter wave communications, energy harvesting, cognitive radio, and wireless security. He currently serves as an Editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technology*, and *IEEE Communications Letters*. He received Best Paper awards at IEEE ICC '14, International Conference on Communications and Networking in China in 2014, and IEEE VTC-Spring 2013. He received the Exemplary Reviewer Certificate of *IEEE Communications Letters* in 2012.

YI QIAN [M'95, SM'07] is an associate professor in the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln (UNL). Prior to joining UNL, he worked in the telecommunications industry, academia, and the government. Some of his previous professional positions include serving as a senior member of scientific staff and technical advisor at Nortel Networks, a senior systems engineer and technical advisor at several startup companies, an assistant professor at the University of Puerto Rico at Mayaguez, and a senior researcher at the National Institute of Standards and Technology. His research interests include information assurance and network security, network design, network modeling, simulation and performance analysis for next generation wireless networks, wireless ad hoc and sensor networks, vehicular networks, smart grid communication networks, broadband satellite networks, optical networks, high-speed networks, and the Internet. He has a successful track record in leading research teams and publishing research results in leading scientific journals and conferences. Several of his recent journal articles on wireless network design and wireless network security are among the most accessed papers in the IEEE Digital Library. He is the current Chair of the Communications and Information Security Technical Committee in the IEEE Communications Society. He is an IEEE Distinguished Lecturer.

TRUNG Q. DUONG received his Ph.D. degree in telecommunications systems from Blekinge Institute of Technology (BTH), Sweden, in 2012, and then continued working at BTH as a project manager. Since 2013, he has joined Queen's University Belfast, United Kingdom, as a lecturer (assistant professor). He held visiting positions at Polytechnic Institute of New York University and Singapore University of Technology and Design in 2009 and 2011, respectively. His current research interests include cooperative communications, cognitive radio networks, green communications, physical layer security, massive MIMO, cross-layer design, mmWave communications, and localization for radios and networks. He has been a TPC chair for several IEEE international conferences and workshops, including most recently the IEEE GLOBECOM '13 Workshop on Trusted Communications with Physical Layer Security. He currently serves as an Editor for *IEEE Communications Letters* and Wiley *Transactions on Emerging Telecommunications Technologies*. He served as Lead Guest Editor of the Special Issue on Location Awareness for Radios and Networks of the *IEEE Journal on Selected Areas in Communications*, Lead Guest Editor of the Special Issue on Secure Physical Layer Communications of *IET Communications*, Guest Editor of the Special Issue on Green Media: Toward Bringing the Gap between Wireless and Visual Networks of *IEEE Wireless Communications*, Guest Editor of the Special Issue on Millimeter Wave Communications for 5G of *IEEE Communications Magazine*, Guest Editor of the Special Issue on Cooperative Cognitive Networks of the *EURASIP Journal on Wireless Communications and Networking*, and Guest Editor of the Special Issue on Security Challenges and Issues in Cognitive Radio Networks of the *EURASIP Journal on Advances Signal Processing*. He was awarded the Best Paper Award at IEEE VTC-Spring '13 and the Exemplary Reviewer Certificate of *IEEE Communications Letters* in 2012.

LEI SHU [M] received his B.Sc. degree in computer science from South Central University for Nationalities, China, in 2002, his M.Sc. degree in computer engineering from Kyung Hee University, Korea, in 2005, and his Ph.D. degree from the Digital Enterprise Research Institute, National University of Ireland, Galway, Ireland, in 2010. Until March 2012, he was a specially assigned researcher in the Department of Multimedia Engineering, Graduate School of Information Science and Technology, Osaka University, Japan. He is a member of IEEE IES, IEEE ComSoc, EAI, and ACM. In October 2012, he joined Guangdong University of Petrochemical Technology, China, as a full professor. In 2013, he started to serve Dalian University of Technology as a Ph.D. supervisor in the College of Software, Beijing University of Posts and Telecommunications as a Master's supervisor in information and communication engineering, Wuhan University as a Master's supervisor in the College of Computer Science, guest professor at Tianjin University of Science and Technology, and a guest researcher at Guangzhou Institute of Advanced Technology, Chinese Academy of Sciences. Meanwhile, he is also working as vice-director of the Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, China. He is the founder of the Industrial Security and Wireless Sensor Networks Lab. HIs research interests include wireless sensor networks, multimedia communication, middleware, fault diagnosis, and security. He has published over 230 papers in related conferences, journals, and books in the area of sensor networks. Currently, his H-index is 21 in Google Citation. Total citations of his papers by other people are more than 1600. He developed an open source wireless sensor networks simulator, NetTopo, to evaluate and demonstrate algorithms. NetTopo has been downloaded more than 3420 times over the past three years, and is widely used by international researchers and students. He was awarded the MASS 2009 IEEE TCs Travel Grant and the Outstanding Leadership Award of EUC 2009 as Publicity Chair, GLOBECOM 2010, and ICC 2013, the ComManTel 2014 Best Paper Award, and the Outstanding Service Award of IUCC 2012 and ComcomAP 2014. He also received a few more awards from the Chinese government: Top Level Talents in "Sailing Plan" of Guangdong Province, China, and Outstanding Young Professor of Guangdong Province, China. He has been serving as Editor-in-Chief for *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, and Associate Editor for *IEEE Access*, ACM/Springer *Wireless Networks*, *Journal of Network and Computer Applications*, *Transactions on Emerging Telecommunications Technology*, and several other publications. He has served as Co-Chair for many international conferences. He has obtained more than 4 million RMB in research grants since October 2012.

FRANK SCHMIDT is a pioneer in energy harvesting and the visionary in the management team of EnOcean. As chief technology officer he is responsible for the overall technical orientation, patent related activities, as well as the relationship management with educational, research and scientific organizations. Before joining EnOcean he was at the Central Research Department of Siemens AG, where he created self-powered wireless sensor technology as early as 1995. He has been granted more than 40 patents for his energy harvesting inventions and is the author of numerous technical publications in this field. He is a physicist and studied at the Technical University of Chemnitz, Germany.