Introduction to the Special Section on Energy-Harvesting Cognitive Radio Networks

WE ARE delighted to introduce the readers to this special section of the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING (TCCN), which has the purpose of addressing fundamental and practical challenges in the analysis and design of energy-harvesting cognitive radio networks (EH-CRNs). We received a total of 19 submissions, and after a rigorous review process, 9 articles have been selected for publication, which are briefly discussed next.

The first article is entitled "Multi-Modal Data Semantic Localization With Relationship Dependencies for Efficient Signal Processing in EH CRNs," authored by Chen *et al.* In this article, multi-media signal processing techniques for EH-CRNs are investigated in which a novel framework for phrases localization is proposed. Tensor factorization method is considered to formulate the approach. Besides, sampling and weighting algorithms are introduced to make the approach robust to unbalanced learning. Experimental results demonstrated that the proposed framework can efficient capture and locate effective information while learning intuitive data associations contained in signals, such that the energy required for subsequent processing and transmission can be greatly reduced.

The second article, entitled "Relay Selections for Cooperative Underlay CR Systems With Energy Harvesting," by Ye *et al.*, investigates the outage performance of three relay selection techniques in cooperative underlay systems with wireless energy harvesting. The distribution of the number of available relay candidates is characterized. Closed-form expressions for the outage probability are derived and insightful discussions are drawn.

In the third article, entitled "Cognitive Wireless Power Transfer in the Presence of Reactive Primary Communication User," Feng *et al.* study a cognitive multi-antenna wireless power transfer (WPT) system over a multicarrier channel which shares the same spectrum band with a primary wireless information transfer (WIT) system that employs adaptive water-filling power allocation. To improve the energy harvesting performance of the energy-hungry node (the S-ER), the secondary WPT system designs the transmit energy beamforming over subcarriers (SCs) to not only directly charge the S-ER, but also control the one-way interference towards the primary information receiver (P-IR), such that the primary information transmitter (P-IT) can reactively adjust its power allocation (based on waterfilling) to facilitate the wireless energy harvesting at the secondary energy receiver (S-ER). An efficient algorithm is designed for the energy beamforming of secondary energy transmitters (S-ETs) over SCs with the aim to maximize the total energy received at the S-ER from both the S-ET and the P-IT, subject to the S-ET's maximum transmit power constraint, and the maximum interference power constraint imposed at the P-IR to protect the primary WIT. The proposed approach provides new insights on the design of coexisting WPT and WIT systems in next-generation self-sustainable IoT networks.

The fourth article, entitled "Sum Throughput Maximization in a Cognitive Multiple Access Channel With Cooperative Spectrum Sensing and Energy Harvesting," by Biswas *et al.*, focuses on the problem of sensing throughput optimization in a fading multiple access cognitive radio (CR) network, where the secondary user (SU) transmitters participate in cooperative spectrum sensing and are capable of harvesting energy and sharing energy with each other. It is formulated an optimization problem as a maximization of the expected achievable sum-rate over a finite horizon, subject to an average interference constraint at the primary receiver, peak power constraints and energy causality constraints at the SU transmitters. The problem is analyzed under two different assumptions on the available information pattern: (i) non-causal channel state information (CSI), energy state information (ESI) and infinite battery capacity, and (ii) the more realistic scenario of the causal CSI/ESI and finite battery. Extensive numerical simulations are carried out to illustrate the performance of the proposed algorithms. One of the main findings indicates that the energy sharing is more beneficial when there is a significant asymmetry between average harvested energy levels/channel gains of different SUs.

The fifth article, entitled "PROLEMus: A Proactive Learning Based MAC Protocol Against PUEA and SSDF Attacks in Energy Constrained Cognitive Radio Networks," by Patnaik *et al.*, proposes a proactive learning based MAC protocol (PROLEMus) that shows immunity to two prominent CR based denial of service (DoS) attacks, namely Primary User Emulation Attack (PUEA) and Spectrum Sensing Data Falsification (SSDF) attack, without any external detection mechanism. PROLEMus shows an average of 6.2%, 8.9% and 12.4% improvement in channel utilization, backoff rate and sensing delay, respectively, with low prediction errors ($\leq$ 1.8%) saving 19.65% energy, when compared to recently proposed MAC protocols like ProMAC aided with additional DoS attack detection mechanism.

The sixth article, entitled "Opportunistic Ambient Backscatter Communication in RF-Powered Cognitive Radio Networks," by Kishore *et al.*, a novel opportunistic ambient backscatter communication (ABC) framework for

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radio frequency (RF)-powered CR networks is proposed. The framework considers opportunistic spectrum sensing integrated with ABC and harvest-then-transmit (HTT) operation strategies. Novel analytical expressions are derived for the average throughput, the average energy consumption and the energy efficiency in the considered set up. It is also formulated an optimization problem to maximize the energy efficiency of the CR system operating in mixed ABC and HTT-modes, for a given set of constraints including primary interference and imperfect spectrum sensing constraints. Extensive results from respective computer simulations are also presented for corroborating the corresponding analytical results and to demonstrate the performance gain of the proposed model in terms of energy efficiency.

In the seventh article, entitled “Age of Information Minimization for an Energy Harvesting Cognitive,” by Leng *et al.*, the average age of information (AoI) minimization in cognitive radio energy harvesting communications is studied. For the energy harvesting cognitive radio who needs to keep the information at its destination as fresh as possible, optimal sensing and update decisions that minimize the average AoI over finite and infinite horizon are considered. Taking into account the partially observable state of the primary user, POMDP is adopted to formulate the average AoI minimization problem subject to the energy causality constraint. For perfect and imperfect spectrum sensing, the partially observable Markov decision processes (POMDPs) are formulated as perfect state information problems, which are solved by dynamic programming. The monotonicity of the value function and the threshold structure of the optimal policy are shown. Numerical results illustrate the policy structures, highlight the impact of energy harvesting system parameters, and demonstrate that optimal policies significantly outperform myopic policies.

The eighth article, by Demarchou *et al.*, entitled “Asynchronous Ad Hoc Networks With Wireless Powered Cognitive Communications,” studies an asynchronous channel access performed by a primary ad hoc network underlaid with a cognitive secondary wireless-powered ad hoc network. It is considered that the primary transmitters are connected to the power grid and employ asynchronous transmissions. On the other hand, the cognitive secondary transmitters have RF energy harvesting capabilities, and their asynchronous channel access is established based on certain energy and interference based criteria. This sporadic channel traffic is modeled with time-space Poisson point processes and by using tools from stochastic geometry. Closed-form expressions for the information coverage probability and the spatial throughput for both networks are derived. Some numerical results are presented and show important insights behind the main system parameters.

Finally, in the last article, entitled “A Joint Optimization Framework for Energy Harvesting Based Cooperative CR Networks,” Ali *et al.* propose resource allocation schemes for EH enabled cooperative CR communication. A two user downlink transmission is adopted where the nearby user helps in relaying the information of faraway user without investing its own energy. A joint optimization over transmission power, time, and PS ratio allocation to maximize the sum rate of the system under battery constraint of BS, minimum rate requirement of each user, and interference temperature constraint of PR is considered. From the analysis, it is observed that the time share optimization under equal power allocation provides higher performance than the power optimization under equal time allocation. However, for small battery power at base station and high rate requirements of users, the power optimization becomes more significant than the time share optimization.

Our Guest Editor team is pleased with the technical depth and span of this Special Section in IEEE TCCN, and also recognizes that it cannot cover all EH-CRN issues inherent to wireless communications and networking. We sincerely thank all the authors and reviewers for the tremendous efforts, and of course the Editor-in-Chief and Staff Members for their great guidance. We hope that the readers will enjoy this special section.

DANIEL BENEVIDES DA COSTA
Federal University of Ceará
Sobral-CE, Brazil
(e-mail: danielbcosta@ieee.org)

GEORGE K. KARAGIANNIDIS
Aristotle University of Thessaloniki
Thessaloniki, Greece
(e-mail: geokarag@auth.gr)

OCTAVIA A. DOBRE
Memorial University
St. John’s, NL, Canada
(e-mail: odobre@mun.ca)

PRABHAT K. UPADHYAY
Indian Institute of Technology Indore
Indore, India
(e-mail: pkupadhyay@iiti.ac.in)

MINGHUA XIA
Sun Yat-sen University
Guangzhou, China
(e-mail: xiamingh@mail.sysu.edu.cn)

HAIYANG DING
National University of Defense Technology
Changsha, China
(e-mail: dinghy2003@hotmail.com)

ROBERT SCHOBER
Alexander University Erlangen–Nuremberg,
Erlangen, Germany
(e-mail: robert.schober@fau.de)

Daniel Benevides da Costa (S'04–M'08–SM'14) was born in Fortaleza, Ceará, Brazil, in 1981. He received the B.Sc. degree in telecommunications from the Military Institute of Engineering (IME), Rio de Janeiro, Brazil, in 2003, and the M.Sc. and Ph.D. degrees in electrical engineering in the area of telecommunications from the University of Campinas, SP, Brazil, in 2006 and 2008, respectively. He was awarded the Best Ph.D. Thesis in Electrical Engineering by the Brazilian Ministry of Education (CAPES) at the 2009 CAPES Thesis Contest. From 2008 to 2009, he was a Postdoctoral Research Fellow with INRS-EMT, University of Quebec, Montreal, QC, Canada. Since 2010, he has been with the Federal University of Ceará, where he is currently an Associate Professor.

He is currently a Senior Editor of IEEE COMMUNICATIONS LETTERS and Editor of IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE ACCESS, IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING, and *EURASIP Journal on Wireless Communications and Networking*. He has also served as an Associate Technical Editor of the *IEEE Communications Magazine*. From 2012 to 2017, he was Editor of IEEE COMMUNICATIONS LETTERS. He has served as an Area Editor of *KSII Transactions on Internet and Information Systems* and as Guest Editor of several journal special issues. He has been involved in the organizing committees of several conferences. He is currently the Latin American Chapter's Coordinator of the IEEE Vehicular Technology Society. Also, he acts as a Scientific Consultant for the National Council of Scientific and Technological Development (CNPq), Brazil, and is a Productivity Research Fellow of CNPq. Currently, he is Vice-Chair of Americas of the IEEE Technical Committee of Cognitive Networks (TCCN), Director of the *TCCN Newsletter*, and Chair of the Special Interest Group on Energy-Harvesting Cognitive Radio Networks in IEEE TCCN.

Prof. da Costa is the recipient of four conference paper awards. He received the Exemplary Reviewer Certificate of the IEEE WIRELESS COMMUNICATIONS LETTERS in 2013, the Exemplary Reviewer Certificate of the IEEE COMMUNICATIONS LETTERS in 2016 and 2017, the Certificate of Appreciation of Top Associate Editor for outstanding contributions to IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY in 2013, 2015, and 2016, the Exemplary Editor Award of IEEE COMMUNICATIONS LETTERS in 2016, and the Outstanding Editor Award of IEEE ACCESS in 2017. He is a Distinguished Lecturer of the IEEE Vehicular Technology Society. He is a Senior Member of IEEE, and a Member of IEEE Communications Society and IEEE Vehicular Technology Society.

George K. Karagiannidis (M'96–SM'03–F'14) was born in Pithagorion, Samos Island, Greece. He received the University Diploma (5 years) and Ph.D. degree, both in electrical and computer engineering from the University of Patras, in 1987 and 1999, respectively. From 2000 to 2004, he was a Senior Researcher at the Institute for Space Applications and Remote Sensing, National Observatory of Athens, Greece. In June 2004, he joined the faculty of Aristotle University of Thessaloniki, Greece where he is currently Professor in the Electrical & Computer Engineering Department and Director of Digital Telecommunications Systems and Networks Laboratory. He is also an Honorary Professor at South West Jiaotong University, Chengdu, China.

His research interests are in the broad area of digital communications systems and signal processing, with emphasis on wireless communications, optical wireless communications, wireless power transfer and applications, communications for biomedical engineering, stochastic processes in biology and wireless security.

He is the author or co-author of more than 500 technical papers published in scientific journals and presented at international conferences. He is also author of the Greek edition of a book *Telecommunications Systems* and co-author of the book *Advanced Optical Wireless Communications Systems*, (Cambridge Publications, 2012).

Dr. Karagiannidis has been involved as General Chair, Technical Program Chair, and member of Technical Program Committees of several IEEE and non-IEEE conferences. He has been Editor of IEEE TRANSACTIONS ON COMMUNICATIONS, Senior Editor of IEEE COMMUNICATIONS LETTERS, Editor of the EURASIP JOURNAL OF WIRELESS COMMUNICATIONS AND NETWORKS and several times Guest Editor of IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. From 2012 to 2015, he was the Editor-in-Chief of IEEE COMMUNICATIONS LETTERS.

Dr. Karagiannidis is a highly-cited author across all areas of electrical engineering, recognized from Clarivate Analytics as Web-of-Science Highly-Cited Researcher in the four consecutive years 2015–2018.

Octavia A. Dobre (M'05–SM'07) received the Dipl.Ing. and Ph.D. degrees from Politehnica University of Bucharest (formerly Polytechnic Institute of Bucharest), Romania, in 1991 and 2000, respectively. Between 2002 and 2005, she was with Politehnica University of Bucharest and New Jersey Institute of Technology, USA. In 2005, she joined Memorial University, Canada, where she is currently Professor and Research Chair. She was a Visiting Professor with Massachusetts Institute of Technology, USA and Université de Bretagne Occidentale, France.

Her research interests include enabling technologies for 5G and beyond, blind signal identification and parameter estimation techniques, as well as optical and underwater communications. She has co-authored more than 250 refereed papers in these areas.

Dr. Dobre serves as the Editor-in-Chief of the IEEE COMMUNICATIONS LETTERS, as well as an Editor of the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS and IEEE SYSTEMS JOURNAL. She has been a Senior Editor, Editor, and Guest Editor for various prestigious journals. She served as General Chair, Tutorial Co-Chair, and Technical Co-Chair at numerous conferences. She was a Royal Society Scholar in 2000 and a Fulbright Scholar in 2001. She is a Distinguished Lecturer of the IEEE Communications Society and a Fellow of the Engineering Institute of Canada.

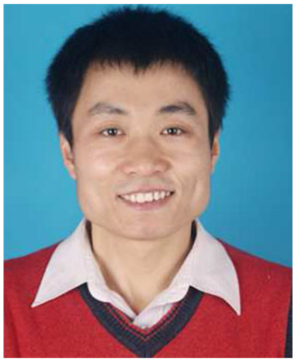
Prabhat K. Upadhyay (S'09–M'13–SM'16) received the Ph.D. degree in electrical engineering from the Indian Institute of Technology (IIT) Delhi, New Delhi, India, in 2011. He was a Lecturer with the Department of Electronics and Communication Engineering, Birla Institute of Technology Mesra, Ranchi. He joined IIT Indore in 2012 as an Assistant Professor in electrical engineering, where he has been an Associate Professor since 2017. He has also leaded various research projects in the Wireless Communications Research Group, IIT Indore. He has numerous publications in peer-reviewed journals and conferences, and has authored a book and three book chapters. He has been awarded the Sir Visvesvaraya Young Faculty Research Fellowship under the Ministry of Electronics and Information Technology, Government of India. He has been conferred the IETE-Prof SVC Aiya Memorial Award-2018.

His main research interests include wireless relaying techniques, cooperative communications, MIMO signal processing, hybrid satellite-terrestrial systems, cognitive radio, and molecular communications. He was a co-recipient of the Best Paper Award at the International Conference on Advanced Communication Technologies and Networking, Marrakech, Morocco, in 2018. He is currently serving as an Editor of IEEE COMMUNICATIONS LETTERS and IEEE ACCESS, and a Guest Editor of the Special Issue on Energy-Harvesting Cognitive Radio Networks in the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING. He has been involved in Technical Program Committee of several premier conferences. He is a Member of the IEEE Communications Society and IEEE Vehicular Technology Society, and a Life Member of the Institution of Electronics and Telecommunication Engineers.

Minghua Xia (M'12) received the Ph.D. degree in telecommunications and information systems from Sun Yat-sen University, Guangzhou, China, in 2007. Since 2015, he has been a Professor with Sun Yat-sen University.

From 2007 to 2009, he was with the Electronics and Telecommunications Research Institute (ETRI) of South Korea, Beijing R&D Center, Beijing, China, where he worked as a member and then as a senior member of the engineering staff. From 2010 to 2014, he was in sequence with The University of Hong Kong, Hong Kong, China; King Abdullah University of Science and Technology, Jeddah, Saudi Arabia; and the Institut National de la Recherche Scientifique (INRS), University of Quebec, Montreal, Canada, as a Postdoctoral Fellow. His research interests are in the general areas of wireless communications and signal processing.

Dr. Xia received the Professional Award at the IEEE TENCON, held in Macau, in 2015. He was also recognized as an Exemplary Reviewer by IEEE TRANSACTIONS ON COMMUNICATIONS in 2014, IEEE COMMUNICATIONS LETTERS in 2014, and IEEE WIRELESS COMMUNICATIONS LETTERS in 2014 and 2015. Currently, he serves as TPC Symposium Chair of IEEE ICC19 and Associate Editor for the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING and the IET SMART CITIES.



Haiyang Ding received the B.Sc. degree in communications engineering from Xi'an Communications Institute, Xi'an, China, in 2003, the M.Sc. degree (with Hons.) in electrical engineering from Beijing University of Technology, Beijing, China, in 2006, and the Ph.D. degree (with Hons.) in telecommunications engineering from Xidian University, Xian, China, in 2013. From 2016 to 2017, he was a Visiting Scholar with the Department of Electronics and Electrical Engineering at Columbia University (CU), New York. Since August 2017, he has been with the School of Information and Communications, National University of Defense Technology (NUDT), where he is currently an Associate Professor. His research interests include energy harvesting, cooperative communications and cognitive radio systems. Currently, he serves as an Editor for *KSII Transactions on Internet and Information Systems*. He was the recipient of the Research in Motion Wireless Research Scholarship from Xidian University in 2012, the IEEE COMMUNICATIONS LETTERS Exemplary Reviewer Certificate in 2013, the IEEE TRANSACTIONS ON COMMUNICATIONS Exemplary Reviewer Certificate in 2014, and the Excellent Ph.D. Dissertation Certificate of Shaanxi Province in 2015.

Robert Schober (F'10) was a Professor and Canada Research Chair at the University of British Columbia (UBC), Vancouver, Canada, from 2002 to 2011. Since 2012, he has been an Alexander von Humboldt Professor and the Chair for Digital Communication at Friedrich-Alexander University Erlangen-Nuremberg (FAU), Germany. His research interests fall into the broad areas of communication theory, wireless communications, and statistical signal processing.

He received several awards for his work including a 2001 Heinz-Maier-Leibnitz Award of the German Science Foundation, a 2007 Wilhelm Friedrich Bessel Research Award of the Alexander von Humboldt Foundation, the 2008 Charles McDowell Award for Excellence in Research from UBC, a 2011 Alexander von Humboldt Professorship, a 2012 NSERC E.W.R. Stacie Fellowship, and the 2017 Wireless Communication Technical Committee Recognition Award. In addition, he has received several best paper awards for his research and is listed as a 2017/2018 Highly Cited Researcher by the Web of Science. He is a Fellow of the Canadian Academy of Engineering, a Fellow of the Engineering Institute of Canada, and a Fellow of the IEEE.

Mr. Schober served as the Editor-in-Chief of the IEEE TRANSACTIONS ON COMMUNICATIONS from 2012 to 2015. Currently, he serves on the Editorial Board of the PROCEEDINGS OF THE IEEE and as the Director of Journals of the IEEE Communications Society (ComSoc). For his service to ComSoc publications, he received the 2018 IEEE ComSoc Joseph LoCiecero Award for Exemplary Service to Publications.