Beyond 5G Wireless Communication Technologies

Yi Qian

The fifth generation (5G) wireless systems have been begun to be widely deployed over the world in recent years. As the 5G technology will not be able to meet the demands of the huge data traffic growth from massively interconnected devices that is forecasted for future years, the attention of the research community is shifting toward what will be the next innovations in wireless communication architectures and technologies for beyond 5G. The topic of beyond 5G wireless communication technologies has gained much momentum in the industry and the research community very recently. In this issue of *IEEE Wireless Communications*, we are pleased to present two Special Issues to bring together researchers, industry practitioners, and individuals working on the related areas to address some of these technical challenges for 5G and beyond wireless communication technologies. The Special Issue on "6G: The Paradigm for Future Wireless Communications" includes a collection of nine articles presented by Guest Editors S. Mumtaz, C. Jiang, A. Tölli, A. Al-Dulaimi, M. Butt, H. M. Asif, and I. Ashraf; the other Special Issue, on "Smart, Optimal, and Explainable Orchestration of Network Slices in 5G and Beyond Networks," includes a collection of five articles presented by Guest Editors Z. M. Fadlullah, M. M. Fouda, K. Rabie, and R. Li. Thanks to the two Guest Editor teams who did an excellent job in editing these two Special Issues for our readers. Please stay tuned for new developments in the research area of beyond 5G wireless communication technologies, and read the editorials and the articles in the Special Issues.

In this issue of the magazine, we are also very glad to present 11 articles accepted from our open call.

The first article, "The Design of User-Centric Mobile Crowdsensing with Cooperative D2D Communications" by S. Yang *et al.*, provides an overview of recent theoretical and practical developments in mobile crowdsensing (MCS) with cooperative device-to-device (D2D) communications. The authors focus on the fundamental challenges for the design of D2D-enabled MCS, covering adaptive sensing and networking, user-transparent and secure D2D connections, and effective incentivization to participating phone users. To further exploit the great potential of D2D-enabled MCS, many research opportunities are also discussed. The authors believe that the development of D2D-enabled MCS could not only greatly support urban big data collection, but also provide valuable insights to other systems with social-aware D2D communications, such as D2D-enabled mobile social networking and mobile cloud computing.

The second article, "Symbiotic Communications: Where Marconi Meets Darwin" by Y.-C. Liang *et al.*, proposes a new symbiotic communication (SC) paradigm through which the relevant radio systems, called symbiotic radios (SRs), in a radio ecosystem form a symbiotic relationship through intelligent resource/service exchange. Radio resources include spectrum, energy, and infrastructure, while typical radio services are communicating, relaying, and computing. The symbiotic relationship can be realized via either symbiotic coevolution or symbiotic synthesis. In symbiotic coevolution, each SR is empowered with an evolutionary cycle alongside multi-agent learning, while in symbiotic synthesis, the SRs ingeniously optimize their operating parameters and transmission protocols by solving a multi-objective optimization problem. The proposed SC paradigm breaks the boundary of radio systems, providing a fresh perspective on radio resource management and new guidelines to design future wireless communication systems.

In the third article, "Grant-Free Random Access in Machine-Type Communication: Approaches and Challenges," J. Choi *et al.* first introduce grant-free random access and discuss how it can be modified with massive multiple-input multiple-output to exploit a high spatial multiplexing gain. The authors then explain preamble designs that can improve the performance and variations based on the notions of semi-grant-free random access and non-orthogonal multiple access. They finally present design challenges of grant-free random access toward next generation cellular systems.

In the fourth article, "6G for Bridging the Digital Divide: Wireless Connectivity to Remote Areas," A. Chaoub *et al.* explore the key challenges associated with constraints on network design and deployment to be addressed for providing broadband connectivity to rural areas, and propose new approaches and solutions for bridging the digital divide in those regions. It is argued that optimally integrating non-terrestrial networks and free space optical technologies can provide low-cost broadband solutions in extremely harsh environments and can be the next disruptive technology for 6G remote connectivity.

In the fifth article, "An Integrated Optimization-Learning Framework for Online Combinatorial Computation Offloading in MEC Networks," X. Li *et al.* provide an overview of the online computation offloading control methods in mobile edge computing systems. They introduce an integrated optimization-learning framework, deep reinforcement learning-based online offloading (DROO), that takes advantage of both past experience and model information to provide fast and robust convergence as well as close-to-optimal real-time offloading control. By incorporating the Lyapunov optimization, the authors demonstrate the flexibility of DROO to solve long-term stochastic online control problems. Furthermore, they highlight several valuable future research topics and discuss the challenges therein.

In the sixth article, "Realizing Ambient Backscatter Communications with Intelligent Surfaces in 6G Wireless Systems," C. Liaskos *et al.* propose the synergy of ambient backscatter communications (aBC) and programmable wireless environments (PWEs). PWEs are shown to promote stable and continuous operation of aBC devices within them by continuously adapting their received power levels and carrier stability. The PWE can facilitate the aBC operation further by handling medium access and operation scheduling duties, creating prospects for more simplified aBC hardware. Finally, they propose a reverse synergy, where dense arrangements of aBC devices can act as metamaterials, creating the prospect of ambient-powered PWEs in the future.

In the seventh article, "Fundamental Wireless Performance of a Building," J. Zhang *et al.* introduce a new and interdisciplinary concept of building wireless performance (BWP) to a wide audience in both wireless communications and building

design, emphasizing its broad impacts on wireless network development and deployment, and on building layout/material design. They first give an overview of the BWP evaluation framework proposed in the state-of-the-art works and explain their interconnections. They then outline the potential research directions in this research area to encourage further interdisciplinary research.

In the eighth article, "Blockchain and 6G: The Future of Secure and Ubiquitous Communication," A. H. Khan *et al.* discuss the potential of blockchain and 6G for future communication and highlight the synergy between them. They divide 6G application requirements into performance-related (RG-I) and security-related (RG-II) groups with the objective of making the synergy more understandable. They show that the trustless nature of blockchain would make it easier to manage and audit 3D network resources and AI model parameters in 6G networks with complex ownership models. This flexible use of increasingly large and complex network resources in 6G with the help of blockchain would significantly facilitate RG-I targets. Through appropriate selection of blockchain type and consensus algorithms, RG-II needs of 6G applications could also be readily addressed. Therefore, blockchain and 6G combined can provide secure and ubiquitous communication.

In the ninth article, "A Path to Smart Radio Environments: An Industrial Viewpoint on Reconfigurable Intelligent Surfaces," R. Liu *et al.* present the latest progress on research, development, and standardization on reconfigurable intelligent surfaces (RISs), and provide some insights on how RISs can be integrated into global standards and commercial networks. Critical challenges down this path are analyzed and possible solutions are suggested.

In the 10th article, "Semantic Communications: Overview, Issues, and Future Research Directions," X. Luo *et al.* give an overview on feature-extraction-based semantic communications, which are relevant to future intelligent communications. Semantic communication works very differently from traditional communication in many aspects, including communication channels, source, channel encoding (decoding) schemes, performance metrics, and so on. The design of an end-to-end semantic communication system is related to the types of messages transmitted, and thus the deep neural network structures of source encoder (decoder) and channel encoder (decoder) can be very different. In particular, the use cases in IoT networks, intelligently connected vehicle networks, and smart factories are discussed for possible implementation of semantic communications. In addition, the open issues are summarized to highlight the challenges in theoretical research and practical implementation of semantic communications.

In the 11th and last article, "Decentralized Spectrum Access System: Vision, Challenges, and a Blockchain Solution," Y. Xiao *et al.* propose a blockchain-based decentralized spectrum access system (SAS) architecture called BD-SAS that provides SAS services securely and efficiently, without relying on the trust of each individual SAS server for the overall system trustworthiness. In BD-SAS, a global blockchain (G-Chain) is used for spectrum regulatory compliance, while smart-contract-enabled local blockchains (L-Chains) are instantiated in individual spectrum zones for automating spectrum access assignment per user request. The authors hope that the vision of a decentralized SAS, the BD-SAS architecture, and discussion of future challenges can open a new direction toward reliable spectrum management in a decentralized manner

I hope you enjoy reading these articles in this issue of *IEEE Wireless Communications*.

Biography

Yi Qian [M'95, SM'07, F'19] received a Ph.D. degree in electrical engineering from Clemson University, South Carolina. He is currently a 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 government. Some of his previous professional positions include serving as a senior member of scientific staff and a technical advisor at Nortel Networks, a senior systems engineer and a 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 wireless communications and networks, and information and communication network security. He has research and industry experience in wireless communications and networks, wireless sensor networks, vehicular communication networks, information and communication network security, smart grid communications, broadband satellite communications, optical communications, high-speed communications and networks, and the Internet of Things. He was previously Chair of the IEEE Technical Committee for Communications and Information Security. He was the Technical Program Chair for IEEE International Conference on Communications 2018. He serves on the Editorial Boards of several international journals and magazines, including as the Editor-in-Chief for *IEEE Wireless Communications*. He was a Distinguished Lecturer for the IEEE Vehicular Technology Society and a Distinguished Lecturer for the IEEE Communications Society. He received the Henry Y. Kleinkauf Family Distinguished New Faculty Teaching Award in 2011, the Holling Family Distinguished Teaching Award in 2012, the Holling Family Distinguished Teaching/Advising/Mentoring Award in 2018, and the Holling Family Distinguished Teaching Award for Innovative Use of Instructional Technology in 2018, all from UNL. He is the principal author of the textbook *Security in Wireless Communication Networks* (IEEE Press/Wiley, 2021).