Guest Editorial Special Issue on Multiple Antenna Technologies for Beyond 5G-Part—I

Jiayi Zhang, *Senior Member, IEEE*, Emil Björnson, *Senior Member, IEEE*, Michail Matthaiou, *Senior Member, IEEE*, Derrick Wing Kwan Ng, *Senior Member, IEEE*, Hong Yang, *Senior Member, IEEE*, and David J. Love, *Fellow, IEEE*

I. Introduction

Recently, the first version of the fifth-generation (5G) new radio (NR) standard with massive multiple-input multiple-output (MIMO) has been finished by the 3rd Generation Partnership Project (3GPP), with initial deployments occurring in 2018. Despite the major advances in 5G, there are still many challenges remaining. 6G and beyond will require even higher data rates, lower latencies, better energy efficiency, and improved robustness. *Multiple antenna technologies,* which have played important roles in nearly all recent wireless standards, will be key to addressing these challenges. MIMO research continues to evolve, and new MIMO research topics such as enhanced massive MIMO techniques and array architectures hold much potential for 6G and beyond. Cell-free massive MIMO utilize a large number of distributed access points (APs) that jointly serve users in a coordinated fashion, using only local channel state information at each AP. While the performance of cell-free massive MIMO can be analyzed using a similar methodology as in cellular massive MIMO, the fundamental limits, signal processing, and resource allocation are substantially different. In order to reduce the hardware cost and energy consumption in millimeter wave (mmWave) massive MIMO systems, beamspace MIMO has been proposed to significantly reduce the number of required radio-frequency (RF) chains by using lens antenna arrays or phase shifters. Alternatively, the intelligent reflecting surface (IRS) concept involves electromagnetically controllable surfaces that can be integrated into large-scale infrastructure such as building walls, airports, and stadiums. There are active and partially passive forms of large intelligent surface (LIS), and variants with either large antenna spacing or continuous aperture. There are also some substantial differences between the new multiple antenna technologies and traditional MIMO systems, such as transceiver design and propagation models. This special issue aims to highlight recent research on multiple antenna technologies.

The call for papers led to a strong response from the multiple antenna research community. This special issue has attracted more than 140 high-quality submissions coming from researchers spread around the world. This is a testament to the widespread interest in multiple antenna research. Due to limited number of available slots, only 39 original contribution papers were eventually selected for publication in a double-issue. All submissions received at least three reviews, and the accepted papers went through at least one revision round.

In this guest editorial paper for the first part of the double issue, we briefly review the research featured in the issue and highlight emerging research themes. The first part of the double issue opens with a paper by the guest editors that highlights major challenges in beyond 5G research and surveys important multiple antenna technology research areas. The contributions of the other papers are categorized as follows.

II. Cell-Free Massive MIMO

The paper "Statistical delay/error-rate bounded QoS provisioning over mmWave cell-free M-MIMO and FBC-HARQ

The work of Jiayi Zhang was supported in part by the National Natural Science Foundation of China under Grant 61971027, in part by the Beijing Natural Science Foundation under Grant 4182049 and Grant L171005, in part by the Science and Technology Key Project of Guangdong Province China under Grant 2019B010157001, and in part by ZTE Corporation. The work of Emil Björnson was supported in part by ELLIIT, and in part by the Swedish Research Council. The work of Michail Matthaiou was supported in part by the Department for the Economy Northern Ireland through the US-Ireland Research and Development Partnership Programme, and in part by the Engineering and Physical Sciences Research Council (EPSRC), U.K., under Grant EP/P000673/1. The work of Derrick Wing Kwan Ng was supported in part by the UNSW Digital Grid Futures Institute, UNSW Sydney, Sydney, through the Cross-Disciplinary Fund Scheme, and in part by the Australian Research Council's Discovery Project under Grant DP190101363. The work of David J. Love was supported in part by the National Science Foundation (NSF) under Grant CCF1816013. *(Corresponding author: Jiayi Zhang.)*

Jiayi Zhang is with the School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China (e-mail: jiayizhang@bjtu.edu.cn).

Emil Björnson is with the Department of Electrical Engineering (ISY), Linköping University, 58183 Linköping, Sweden (e-mail: emil.bjornson@liu.se).

Michail Matthaiou is with the Institute of Electronics, Communications and Information Technology (ECIT), Queen's University Belfast, Belfast BT3 9DT, U.K. (e-mail: m.matthaiou@qub.ac.uk).

Derrick Wing Kwan Ng is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: w.k.ng@unsw.edu.au).

Hong Yang is with Nokia Bell Laboratories, Murray Hill, NJ 07974 USA (e-mail: h.yang@nokia-bell-labs.com).

David J. Love is with the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907 USA (e-mail: djlove@purdue.edu).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSAC.2020.3001817

based 5G+ mobile wireless networks" addresses quality-of-service (QoS) provisioning in mmWave cell-free massive MIMO, with a focus on statistical delay/error-rate bounded performance. The authors show how to use a hybrid automatic repeat request with incremental redundancy protocol to analyze the capacity and characterize QoS metrics via error probability.

The paper "Exploiting deep learning in limited-fronthaul cell-free massive MIMO uplink" considers a cell-free massive MIMO uplink based on quantize-and-forward. Here the signals received at the APs are quantized and forwarded to a central processing unit. The paper utilizes a deep convolutional neural network technique to derive optimal user transmit powers.

The paper "On the spectral and energy efficiencies of full-duplex cell-free massive MIMO" formulates an optimization framework for the maximization of both spectral efficiency (SE) and energy efficiency (EE) in cell-free massive MIMO systems. In the framework, power control, user association and AP selection are jointly optimized using a realistic power consumption model, which results in an interesting mixed-integer nonconvex programming. The authors develop simple iterative algorithms with polynomial computational complexity in each iteration and provide theoretical analysis by combining an inner approximation framework and the Dinkelbach method.

III. Intelligent Reflecting Surfaces

The paper "Intelligent reflecting surface aided MIMO broadcasting for simultaneous wireless information and power transfer" addresses simultaneous wireless information and power transfer (SWIPT) with an IRS. The paper considers a multiple antenna base station communicating with several multiple antenna information receivers, subject to energy harvesting requirements imposed on the energy receivers. The transmit precoding matrices and IRS passive phase shift matrix are jointly optimized using block coordinate descent and a low-complexity iterative algorithm to increase the weighted sum rate.

The paper "Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints" also addresses IRS-assisted SWIPT. The authors aim to minimize the transmit power by jointly optimizing the transmit precoders and the phase shifts at all IRSs, while requiring QoS constraints for the users. The optimization problem is solved by applying proper transformations on the QoS constraints and the penalty-based optimization method. It demonstrates the effectiveness of employing multiple IRSs to increase the SWIPT system performance.

The paper "Stochastic geometry analysis of large intelligent surface-assisted millimeter wave networks" analyzes a two-step user association in a mmWave network using stochastic geometry. The paper's framework includes a one-hop reflection from an LIS, and the results demonstrate that an LIS-assisted network can attain a capacity enhancement and higher energy efficiency as compared to traditional systems when the density of BSs is not large.

The paper "Programmable metasurface based multicast systems: Design and analysis" considers a multi-antenna multicast system with a programmable metasurface (PMS) at the transmitter. A novel training approach is proposed that takes into account the finite-resolution phase shifts of the PMS and achieves performance comparable to an exhaustive beam search with lower time overhead. Closed-form solutions are derived for the optimal power control coefficients and multicast rate for several asymptotic scenarios.

The paper "MIMO detection for reconfigurable intelligent surface-assisted millimeter wave systems" develops a MIMO detector using characteristics of the synthetic channel. The authors analyze the bit error rate of the proposed detector for several scenarios using state evolution equations. The results demonstrate that the low-cost hardware can be employed with only moderate degradation of the system performance.

The paper "Passive beamforming and information transfer design for reconfigurable intelligent surfaces aided multiuser MIMO systems" proposes a passive beamforming and information transfer technique for multiuser MIMO systems using reconfigurable intelligent surfaces (RISs). The RISs enhance the communication via passive beamforming and deliver additional information using on-off reflecting modulation conveyed through the on/off state of each reflecting element. The paper discusses a sample average approximation-based iterative algorithm, and a turbo message passing algorithm is developed to decode the information from both the users and the RIS in the system.

The paper "Hybrid beamforming for reconfigurable intelligent surface based multi-user communications: Achievable rates with limited discrete phase shifts" studies a downlink multiuser system with a multiple antenna base station communicating with users. The system uses an RIS to enhance the signal sent to the users. The paper also proposes a hybrid beamforming scheme, and the sum-rate is maximizes using an iterative algorithm. The paper shows that an RIS-based system can achieve an improved sum-rate using a reasonably-sized RIS with a small number of discrete phase shifts.

The paper "Capacity characterization for intelligent reflecting surface aided MIMO communication" aims to characterize the fundamental limits of an IRS-aided point-to-point MIMO communication system by jointly optimizing the IRS reflection coefficients and the transmit covariance matrix. The results show that various measures of performance (e.g., channel total power, rank, and condition number) are improved using the developed techniques.

The paper "Reconfigurable intelligent surface assisted multi-user MISO systems exploiting deep reinforcement learning" investigates the joint design of beamforming and the RIS phase shift matrix by utilizing recent deep reinforcement learning (DRL) techniques. The paper's DRL-based algorithm performs the joint design using a DRL neural network. This scheme provides comparable performance to existing techniques and is able to adapt to its operational environment.

IV. MIMO Meets Others

The paper "Massive MIMO transmission for LEO satellite communications" looks at applying massive MIMO with full frequency reuse to low earth orbit satellite communication. Obtaining accurate CSI is difficult in this scenario, and the framework exploits statistical channel state information to overcome this challenge. The authors also propose a technique called space angle based user grouping to schedule the users via a grouping technique. The paper claims that the proposed techniques lead to an increased data rate.

The paper "Simultaneous position and orientation estimation for visible light systems with multiple LEDs and multiple PDs" discusses the simultaneous position and orientation estimation problem in a visible light system consisting of multiple light emitting diodes and multiple photodiodes. The authors study solutions using received signal strength measurements. The paper shows that the proposed algorithms are asymptotically tight to the theoretical lower bound.

The paper "Hybrid transceiver optimization for multi-hop communications" studies a MIMO multi-hop set-up using amplify-and-forward with hybrid transceivers. The optimal structures for the hybrid and digital transceivers are derived using matrix-monotonic optimization. The proposed hybrid set-up is shown to outperform existing solutions.

The paper "Monostatic MIMO backscatter communications" investigates the backscatter communication with a MIMO monostatic channel. The maximum achievable diversity order is shown to be obtained using a block-lever unitary query and orthogonal space-time block code. In contrast to traditional MIMO thinking, it is also shown that additional diversity is possible by modifying the query signals over the time slots during the channel coherence time.

The paper "Rate splitting for multi-antenna downlink: Precoder design and practical implementation" looks at rate splitting in its most general form using multiple streams and joint decoding for a multiple antenna base station and multiple single-antenna users. The analysis in the paper shows that rate splitting can provide significant gain compared to the performance of advanced linear precoding schemes, particularly for the case of a large number of users.

The paper "Green communications for multi-cell MISO-NOMA systems: A joint user grouping, beamforming and power control perspective" studies power minimization in a generic multi-cell multiple-input single-output nonorthogonal multiple access (MISO-NOMA) framework. The paper looks at the performance measures of power consumption, outage probability, energy efficiency, and connectivity efficiency, and it proposes a resource management solution that outperforms conventional MISO schemes and non-clustered MISO-NOMA.

V. Conclusion and Acknowledgement

In conclusion, the guest editors feel that the special issue provides valuable insights into current and future research areas focused on multiple antenna technologies. The guest editors deeply appreciate the help provided by Prof. Larry Milstein. His valuable advice was critical to the success of this special issue. The guest editors also wish to thank Janine Bruttin for her help in preparing the special issue in a timely way. The guest editors also wish to thank the authors and reviewers for their efforts to ensure this is a high-quality and relevant special issue.

Jiayi Zhang (Senior Member, IEEE) received the B.Sc. degree and the Ph.D. degree in communication engineering from Beijing Jiaotong University, China, in 2007 and 2014, respectively.

Since 2016, he has been a Professor with the School of Electronic and Information Engineering, Beijing Jiaotong University. From 2014 to 2016, he was a Post-Doctoral Research Associate with the Department of Electronic Engineering, Tsinghua University, China. From 2014 to 2015, he was also a Humboldt Research Fellow with the Institute for Digital Communications, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany. From 2012 to 2013, he was a Visiting Scholar with Wireless Group, University of Southampton, U.K. His current research interests include massive MIMO, large intelligent surface, communication theory, and applied mathematics. He received the Best Paper Awards at the WCSP 2017 and IEEE APCC 2017. He was recognized as an Exemplary Reviewer of the IEEE Communications Letters in 2015 and 2016 and the IEEE Transactions on Communications in 2017. He was the Lead Guest Editor of the Special Issue on Multiple Antenna Technologies for Beyond 5G of the IEEE Journal on Selected Areas in Communications. He is currently serving as an Associate Editor for the IEEE Transactions on Communications, the IEEE Communications Letters, the IEEE Access, and *IET Communications*.

Emil Björnson (Senior Member, IEEE) received the M.S. degree in engineering mathematics from Lund University, Sweden, in 2007, and the Ph.D. degree in telecommunications from the KTH Royal Institute of Technology, Sweden, in 2011.

From 2012 to 2014, he held a joint post-doctoral position at the Alcatel-Lucent Chair on Flexible Radio, Supélec, France, and the KTH Royal Institute of Technology. He joined Linköping University, Sweden, in 2014, where he is currently an Associate Professor and a Docent with the Division of Communication Systems. He has authored the textbooks *Optimal Resource Allocation in Coordinated Multi-Cell Systems* in 2013 and *Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency* in 2017. He is dedicated to reproducible research and has made a large amount of simulation code publicly available. He performs research on MIMO communications, radio resource allocation, machine learning for communications, and energy efficiency. Since 2017, he has been on the Editorial Board of the IEEE Transactions on Communications and the IEEE Transactions on Green Communications and Networking since 2016. He has performed MIMO research for over 10 years and has filed more than 20 MIMO related patent applications.

Dr. Björnson received the 2014 Outstanding Young Researcher Award from the IEEE ComSoc EMEA, the 2015 Ingvar Carlsson Award, the 2016 Best Ph.D. Award from EURASIP, the 2018 IEEE Marconi Prize Paper Award in Wireless Communications, the 2019 EURASIP Early Career Award, the 2019 IEEE Communications Society Fred W. Ellersick Prize, and the 2019 IEEE Signal Processing Magazine Best Column Award. He also coauthored articles that received Best Paper Awards at the conferences, including WCSP 2009, the IEEE CAMSAP 2011, the IEEE WCNC 2014, the IEEE ICC 2015, WCSP 2017, and the IEEE SAM 2014.

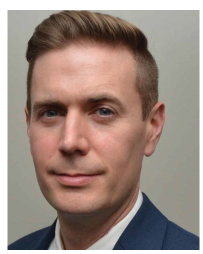
Michail Matthaiou (Senior Member, IEEE) was born in Thessaloniki, Greece, in 1981. He received the Diploma degree in electrical and computer engineering from the Aristotle University of Thessaloniki, Greece, in 2004, the M.Sc. degree (Hons.) in communication systems and signal processing from the University of Bristol, U.K., in 2005, and the Ph.D. degree from The University of Edinburgh, U.K., in 2008.

From September 2008 to May 2010, he was with the Institute for Circuit Theory and Signal Processing, Technical University of Munich (TUM), Germany, working as a Post-Doctoral Research Associate. He is currently a Reader (equivalent to Associate Professor) of multiple-antenna systems with Queen's University Belfast, U.K., after holding an assistant professor position at the Chalmers University of Technology, Sweden. His research interests include signal processing for wireless communications, massive MIMO systems, hardware-constrained communications, mm-wave systems, and deep learning for communications. He and his coauthors received the IEEE Communications Society (ComSoc) Leonard G. Abraham Prize in 2017. He was awarded the prestigious 2018/2019 Royal Academy of Engineering/Leverhulme Trust Senior Research Fellowship and recently received the 2019 EURASIP Early Career Award. His team was also the Grand Winner of the 2019 Mobile World Congress Challenge. He was a recipient of the 2011 IEEE ComSoc Best Young Researcher Award for the Europe, Middle East, and Africa Region and a co-recipient of the 2006 IEEE Communications Chapter Project Prize for the Best M.Sc. Dissertation in the area of communications. He has coauthored articles that received Best Paper Awards at the 2018 IEEE WCSP and 2014 IEEE ICC and was an Exemplary Reviewer of the IEEE COMMUNICATIONS LETTERS in 2010. In 2014, he received the Research Fund for International Young Scientists from the National Natural Science Foundation of China. He is currently the Editor-in-Chief of *Physical Communication* (Elsevier) and a Senior Editor of the IEEE WIRELESS COMMUNICATIONS LETTERS. He was an Associate Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS and an Associate Editor/Senior Editor of the IEEE COMMUNICATIONS LETTERS.

Hong Yang (Senior Member, IEEE) received the Ph.D. degree in applied mathematics from Princeton University, Princeton, NJ, USA. He was involved in academia and a start-up network technology company before joining Lucent Technologies Inc., and Alcatel-Lucent, where he was with Wireless Design Center, Systems Engineering Department, and Bell Labs Research, Murray Hill, NJ, USA. He is currently a Member of Technical Staff with the Mathematics of Networks and Communications Research Department, Nokia Bell Laboratories, where he conducts research in communications networks. He has coauthored many research articles in wireless communications, applied mathematics, control theory, and financial economics. He co-invented many U.S. and international patents. He coauthored the book *Fundamentals of Massive MIMO* (Cambridge University Press, 2016).

Derrick Wing Kwan Ng (Senior Member, IEEE) received the bachelor's degree (Hons.) and the M.Phil. degree in electronic engineering from The Hong Kong University of Science and Technology (HKUST) in 2006 and 2008, respectively, and the Ph.D. degree from The University of British Columbia (UBC) in 2012.

He was a Senior Post-Doctoral Fellow with the Institute for Digital Communications, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany. He is currently working as a Senior Lecturer and a Scientia Fellow with the University of New South Wales, Sydney, NSW, Australia. His research interests include convex and nonconvex optimization, physical layer security, IRS-assisted communications, UAV-assisted communications, wireless information and power transfer, and green (energy-efficient) wireless communications. He received the Best Paper Awards at the IEEE TCGCC Best Journal Paper Award 2018, INISCOM 2018, the IEEE International Conference on Communications (ICC) 2018, the IEEE International Conference on Computing, Networking and Communications (ICNC) 2016, the IEEE Wireless Communications and Networking Conference (WCNC) 2012, the IEEE Global Telecommunication Conference (Globecom) 2011, and the IEEE Third International Conference on Communications and Networking in China 2008. He has been serving as an Editorial Assistant to the Editor-in-Chief of the IEEE TRANSACTIONS ON COMMUNICATIONS from January 2012 to December 2019. He is also serving as an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS and the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and an Area Editor for the IEEE OPEN JOURNAL OF THE COMMUNICATIONS SOCIETY. He is also listed as a Highly Cited Researcher by Clarivate Analytics in 2018 and 2019.



David J. Love (Fellow, IEEE) received the B.S. (Hons.), M.S.E., and Ph.D. degrees in electrical engineering from The University of Texas at Austin in 2000, 2002, and 2004, respectively.

Since 2004, he has been with the School of Electrical and Computer Engineering, Purdue University, where he is currently the Nick Trbovich Professor of electrical and computer engineering and also leads the College of Engineering Preeminent Team on Efficient Spectrum Usage. He holds 31 issued U.S. patent filings. His research interests include the design and analysis of broadband wireless communication systems, 5G wireless systems, multiple-input–multiple-output (MIMO) communications, millimeter wave wireless, software-defined radios and wireless networks, coding theory, and MIMO array processing. He is a member of the Executive Committee for the National Spectrum Consortium. He is a fellow of the Royal Statistical Society and has been inducted into the Tau Beta Pi and the Eta Kappa Nu. Along with his coauthors, he won the Best Paper Awards from the IEEE Communications Society (the 2016 IEEE Communications Society Stephen O. Rice Prize), the IEEE Signal Processing Society (the 2015 IEEE Signal Processing Society Best Paper Award), and the IEEE Vehicular Technology Society (the 2009 IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY Jack Neubauer Memorial Award). He also serves as a Senior Editor for *IEEE Signal Processing Magazine* and previously served as an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, an Associate Editor for the IEEE TRANSACTIONS ON SIGNAL PROCESSING, and a Guest Editor for Special Issues of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS and the *EURASIP Journal on Wireless Communications and Networking*. He was named as a Thomson Reuters Highly Cited Researcher in 2014 and 2015.