Guest Editorial Rate Splitting for Future Wireless Networks

Bruno Clerckx, *Fellow, IEEE*, Yijie Mao, *Member, IEEE*, Eduard A. Jorswieck, *Fellow, IEEE*, Jinhong Yuan, *Fellow, IEEE*, David J. Love, *Fellow, IEEE*, Elza Erkip, *Fellow, IEEE*, and Dusit Niyato, *Fellow, IEEE*

RATE splitting (RS) and rate splitting multiple access (RSMA) have emerged as a promising and powerful multiple access, interference management, and multi-user strategy for next-generation wireless systems and networks. This Special Issue is entirely dedicated to the theory, design, optimization, and applications of RS and RSMA in various network configurations. It starts with a guest editor-authored tutorial paper [A1] that delineates the basic principles and applications of RS and RSMA. The tutorial paper is then followed by 17 technical papers.

The tutorial paper provides a primer on RS and RSMA. Uniquely, it delves into the fundamentals of interference management and related role of RS and shows how multi-user communications and multiple access design for 6G and beyond should be intimately related to the crucial problem of efficiently managing interference. The discussion opens the door to a deeper understanding of multiple access design and how to classify multiple access schemes as a function of their interference management capabilities. This eliminates the confusion induced by amalgamating unrelated schemes under the non-orthogonal multiple access (NOMA) umbrella and goes beyond the oversimplistic comparison between orthogonal multiple access (OMA) and NOMA, as done in the 5G days. The RSMA frameworks for downlink, uplink, and multi-cell networks are then described and shown to offer numerous benefits for 6G and beyond: enhanced spectral, energy and computation efficiency; universality by unifying and generalizing OMA, NOMA, space-division multiple access (SDMA), physical-layer multicasting; flexibility by coping with any interference levels, network loads, services, traffic, user deployments; robustness to inaccurate channel state information and resilience to mixed-critical quality of service; reliability under short channel codes and low latency. Those benefits are then exemplified in 40 scenarios and applications relevant in 6G. The tutorial finishes with a discussion on myths, frequently asked questions, and the underpinning role played by RSMA in next-generation networks [A1].

Next, 17 technical papers are presented. Given the underpinning role that RS/RSMA can play in future networks, those papers cover a wide range of topics and applications, ranging from information-theoretic limits involving RS; game theory approaches for RS design and optimization; communication theoretic issues of rate-splitted (cell-free, massive) multiple-input multiple-output (MIMO) networks; RS in reconfigurable intelligent surfaces; interplay between RS schemes, federated/machine learning, and semantic communications; RS role in integrated sensing and communications; RS in virtual reality; RS for cloud and edge computing.

Information Theory Limits Involving RS

Wang and Jafar [A2] consider the $2 \times 2 \times 2$ interference channel, consisting of two sources, two relays, and two destinations. The authors fully characterize the generalized degree-of-freedom (GDoF) of the scenario in which the channel state information at the transmitter (CSIT) is finite precision, the interference is weak and the channel gains are heterogeneous (symmetric in each hop, but different across hops). Their achievable strategy uses sophisticated rate-splitting arguments along with decode-and-forward, amplify-and-forward and quantize-and-forward relaying schemes, and their converse is based on sum-set inequalities and aligned image sets.

Game Theory Approaches for RS

Nguyen et al. [A3] study dynamic network resource selection in RSMA-enabled cellular network. First, users select their favorite resource blocks over time. Next, users in one resource block perform RSMA and maximize their sum rate by a sequential convex approximation algorithm. The traditional and fractional evolutionary game models are applied for the resource selection process. Analytical results regarding replicator dynamics and stability of the equilibrium are derived.

Bruno Clerckx is with the Department of Electrical and Electronic Engineering, Imperial College London, SW7 2AZ London, U.K., and also with Silicon Austria Labs (SAL), 8010 Graz, Austria (e-mail: b.clerckx@imperial.ac.uk).

Yijie Mao is with the School of Information Science and Technology, ShanghaiTech University, Shanghai 201210, China (e-mail: maoyj@shanghaitech.edu.cn).

Eduard A. Jorswieck is with the Institute for Communications Technology, TU Braunschweig, 38106 Braunschweig, Germany (e-mail: e.jorswieck@tu-bs.de).

Jinhong Yuan is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: j.yuan@unsw.edu.au).

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

Elza Erkip is with the Department of Electrical and Computer Engineering, New York University Tandon School of Engineering, Brooklyn, NY 11201 USA (e-mail: elza@nyu.edu).

Dusit Niyato is with the School of Computer Science and Engineering, Nanyang Technological University, Singapore 639798 (e-mail: dniyato@ntu.edu.sg).

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The numerical assessments illustrate the convergence and performance. Interestingly, taking past decisions into account, the fractional evolutionary outperforms the traditional approach.

RS-Aided (Massive) MIMO Networks

Mosquera and Gómez-Cuba [A4] consider the embedding of link adaptation into the operation of a MIMO broadcast channel which makes use of RS precoding. They characterize the outage rate region of RS and analyze the convergence of the complete link adaptation-RS system under partial CSIT, providing relevant insights for addressing the adaptation of private and common rates, designing robust precoders with throughput as relevant metric, and handling the time-variant CSIT quality. From the convergence analysis, it is concluded that the adaptation speed of the back-off private and common margins determines the stationary point; additionally, the periodic update of CSIT and recalculation of precoders gives rise to a periodic behavior of the margins to enforce the prescribed average error probability.

Amor et al. [A5] study the use of RSMA in massive MIMO systems using frequency-division-duplex (FDD) communication. They formulate a sum rate optimization problem depending on the channel statistics and using the assumption of bilinear precoding. A multi-step optimization solution is proposed. Because the algorithm is based on channel distribution information (CDI) only, there are numerous benefits when deployed in an FDD scenario. The numerical results, which include a comparison with iterative weighted minimum mean squared error (IWMMSE) precoding, show that the algorithm offers achievable sum rate benefits.

Zheng et al. [A6] derive closed-form expressions for the spectral efficiencies of cell-free massive MIMO networks taking propagation delays and oscillator phase noise into account both with and without RS. It is shown that asynchronous reception destroys the pilot orthogonality and coherent data transmission resulting in poor system performance. In addition, the robust precoding of common message is modeled and solved by bisection globally. The numerical assessments show the performance gain of RS. Under severe asynchronous signal reception, robust precoding is necessary for the common messages in RS. The proposed robust precoding performs well in some extreme scenarios

Jiang et al. [A7] focus on the emerging area of user electromagnetic (EM) exposure-aware communication. The authors investigate multiuser massive MIMO systems that use uplink RSMA. They discuss an energy efficiency (EE) cost function and formulate an optimization problem based on maximizing EE subject to EM exposure constraints. The user transmit covariance and decoding order optimization is formulated as an inner and outer optimization. The numerical results show the EE benefits provided by the developed RSMA approach.

Wang et al [A8] consider a downlink multi-input, single-output (MISO) channel and propose a flexible RSMA scheme in which some users (called "RS users") enjoy the benefits of RSMA by decoding a common stream followed by successive interference cancelation, while other users only decode their own private streams by treating the common stream as noise. The authors study the effective throughput of this scheme in the finite blocklength regime. To increase the effective throughput, they carry out a joint optimization over the beamforming vectors, transmission data rates, and RS-user selection. They show that the proposed scheme outperforms both the conventional SDMA and NOMA in the regime of interest.

RS With Reconfigurable Intelligent Surfaces

Zhang et al. [A9] investigate the synergizing of reconfigurable intelligent surface (RIS)-aided simultaneous wireless information and power transfer (SWIPT) networks and RSMA considering a non-linear energy harvesting model and discrete RIS phase shifts. With a focus on maximizing the system EE, the authors propose a novel deep reinforcement learning (DRL)-based approach to jointly design the transmit beamforming, power splitting ratios, common message allocation and discrete phase shifts. Specifically, the formulated optimization problem is first transformed into a Markov decision process, which is then solved by a new proximal policy optimization (PPO)-based DRL approach. To evaluate the performance of the proposed PPO-based DRL algorithm, an EE upper-bound optimization problem is also formulated and solved by the conventional alternative optimization-based approach. The simulation results show that the system EE obtained by the proposed PPO-based approach is close to the EE upper-bound and outperforms various benchmarks at a much lower computational time. Moreover, RSMA significantly enhances EE compared with the conventional linearly precoded space-division multiple access (SDMA).

Wu et al. [A10] propose a deep-learning (DL)-based RSMA scheme for RIS-aided Tera-Hertz multi-user MIMO systems. This involves several optimization steps: to design the RIS matrix, a RIS reflecting network (RRN) based on the emerging Transformer structure is developed which effectively extracts the correlation features of multiple subcarriers of the MIMO-OFDM channel; for the RSMA digital precoding, an approximate weighted MMSE precoding is combined with DL which provides good performance under imperfect CSI, interpretability, predictability, and fast convergence; the joint optimization of the passive precoding at the RIS and the RSMA active precoding at the base station (BS) is performed by end-to-end (E2E) training; for channel estimation, the transformer structure is introduced to form an E2E channel acquisition network (CAN) trained to minimize normalized MSE. The numerical assessments show that the proposed DL-based RSMA precoding scheme can stably outperform the conventional schemes and the proposed CAN can accurately estimate the downlink RIS-UE CSI at the BS with low pilot and feedback signaling overhead.

Niu et al. [A11] study the combination of RSMA with a RIS, with a focus on spectral efficiency (SE) and EE. To accommodate the tradeoff between SE and EE, the authors utilize the resource efficiency (RE) metric. A RE optimization problem over both the transmit precoding and RIS operation is formulated. An alternating optimization algorithm for the

precoders and RIS operation is proposed. Convergence behavior and RE behavior are numerically studied.

RS, Machine Learning and Semantic Communications

Zhang et al. [A12] show how the high spectral efficiency, robustness to channel state information imperfections, and security guarantees offered by RSMA are helpful in high-velocity vehicular platoons. They developed a RSMA-based Internet of Vehicles (IoV) solution that jointly considers platoon control and federated edge learning. The solution is optimized using a combination of Block Coordinate Descent, Successive Convex Approximation, and Model Predictive Control. The simulation results demonstrate that the RSMA-based IoV system outperforms both SDMA and NOMA counterparts.

Yang et al. [A13] consider a downlink semantic information communication setting in which a base station first extracts semantic information, and then uses RS to send the common part through a common message and individual small-sized semantic information through private messages to each user. The users utilize their local knowledge to ultimately recover the original data. The authors formulate an optimization problem where they consider the computation energy in addition to the transmit energy. The goal of the optimization is to minimize total energy under latency constraints. An iterative algorithm is proposed to solve this optimization and its effectiveness is illustrated through numerical results.

RS in Integrated Sensing and Communications

Gao et al. [A14] study a cooperative ISAC (CoISAC) system with a RSMA transmission scheme, which incorporated advanced interference management and direct localization sensing to significantly enhance accuracy of positioning services. A Pareto optimization framework is formulated to characterize the achievable performance region of CoISAC system, in terms of the sum rate of multiple communication users and position estimation error bound of radar target. In particular, communication-centric and radar-centric optimization problems in the proposed CoISAC system are investigated to find the optimal performance trade-offs. The authors show that the cooperative scheme can offer more flexibility and freedom for rate-splitting policy design, boosting the overall system performance.

RS for Virtual Reality

Huang et al. [A15] propose an intelligent reflecting surface (IRS)-aided RS virtual reality (VR) streaming system, in which RS facilitates the exploitation of the shared interests of the users in VR streaming and IRS creates additional propagation channels to support the transmission of high-resolution 360-degree videos. They formulate an optimization problem for maximization of the achievable bitrate of the 360-degree video subject to the quality-of-service (QoS) constraints of the users. A deep deterministic policy gradient with imitation learning algorithm is proposed to optimize the IRS phase shifts, RS parameters, beamforming vectors, and bitrate selection of the 360-degree video tiles. Performance evaluation shows that the proposed IRS-aided RS VR streaming system outperforms several baseline schemes in terms of system sum-rate, achievable bitrate of the 360-degree videos, and online execution runtime.

Hieu et al. [A16] consider a virtual reality streaming application that uses RSMA for interference management. The authors formulate a joint communication and computation problem for effective resource management. Users are clustered based on their Field-of-View metric, and a hierarchical RS scheme is adopted to serve user clusters. In addition, a deep reinforcement learning algorithm that adapts the power and computing resource allocation to the dynamic user environment is proposed. The numerical results demonstrate the effectiveness of the proposed methods in the envisioned low-latency 360-degree wireless video streaming applications.

RS for Cloud and Edge Computing

Chen et al. [A17] proposed a RSMA-aided mobile edge computing (MEC) scheme for future communication networks in order to offload users' computation tasks to a MEC server. Specifically, a cognitive radio (CR)-inspired rate-splitting is designed to enable the paired users to attain the maximum achievable rate for the secondary user, meanwhile maintaining the primary user's offloading performance same as in orthogonal multiple access. This article considers various offloading scenarios including complete offloading, fully local computation, and partial offloading. The closed-form successful computation probability (SCP) expression is shown to characterize the offloading performance and clarify the superior offloading performance achieved by the RSMA-MEC scheme.

Reifert et al. [A18] propose, and evaluate the benefits of, a hybrid central cloud (CC) and mobile edge computing (MEC) platform, specially introduced to balance the network resources for joint communication and computation. They then considers the problem of maximizing the weighted sum-rate subject to fronthaul and computation capacity, achievable rates, power, delay, and data-split constraints. Such intricate non-convex optimization problem is tackled using an iterative algorithm that relies on well-chosen discrete relaxation, successive convex approximation, and fractional programming, and can be compellingly implemented in a distributed fashion. The simulations illustrate the proposed algorithm's capabilities for empowering joint communication and computation.

The tutorial paper and the 17 papers in this Special Issue provide an overview of the state-of-the-art as well as new results in the broad area of RS/RSMA theory and applications. The breadth of the topics reported in this issue demonstrates the interest of the community in this active research area. It is our hope that this Special Issue will stimulate and encourage further research in the broad area of RS/RSMA for future wireless networks.

APPENDIX: RELATED ARTICLES

[A1] B. Clerckx et al., "A primer on rate-splitting multiple access: Tutorial, myths, and frequently asked questions," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1265–1308, May 2023.

[A2] J. Wang and S. A. Jafar, "Robust sum-GDoF of symmetric 2 × 2 × 2 weak interference channel with heterogeneous hops," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1309–1319, May 2023.

[A3] N. T. Thanh Van, N. C. Luong, S. Feng, V.-D. Nguyen, and D. I. Kim, "Evolutionary games for dynamic network resource selection in RSMA-enabled 6G networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1320–1335, May 2023.

[A4] C. Mosquera and F. Gomez-Cuba, "Link adaptation for rate splitting systems with partial CSIT," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1336–1350, May 2023.

[A5] D. B. Amor, M. Joham, and W. Utschick, "Rate splitting in FDD massive MIMO systems based on the second order statistics of transmission channels," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1351–1365, May 2023.

[A6] J. Zheng, J. Zhang, J. Cheng, V. C. M. Leung, D. W. K. Ng, and B. Ai, "Asynchronous cell-free massive MIMO with rate-splitting," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1366–1382, May 2023.

[A7] H. Jiang et al., "Rate-splitting multiple access for uplink massive MIMO with electromagnetic exposure constraints," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1383–1397, May 2023.

[A8] Y. Wang, V. W. S. Wong, and J. Wang, "Flexible rate-splitting multiple access with finite blocklength," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1398–1412, May 2023.

[A9] R. Zhang, K. Xiong, Y. Lu, P. Fan, D. W. K. Ng, and K. B. Letaief, "Energy efficiency maximization in RIS-assisted SWIPT networks with RSMA: A PPO-based approach," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1413–1430, May 2023.

[A10] M. Wu, Z. Gao, Y. Huang, Z. Xiao, D. W. K. Ng, and Z. Zhang, "Deep learning-based rate-splitting multiple access for reconfigurable intelligent surface-aided tera-hertz massive MIMO," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1431–1451, May 2023.

[A11] H. Niu et al., "Active RIS assisted rate-splitting multiple access network: Spectral and energy efficiency tradeoff," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1452–1467, May 2023.

[A12] S. Zhang, S. Zhang, W. Yuan, Y. Li, and L. Hanzo, "Efficient rate-splitting multiple access for the Internet of Vehicles: Federated edge learning and latency minimization," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1468–1483, May 2023.

[A13] Z. Yang, M. Chen, Z. Zhang, and C. Huang, "Energy efficient semantic communication over wireless networks with rate splitting," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1484–1495, May 2023.

[A14] P. Gao, L. Lian, and J. Yu, "Cooperative ISAC with direct localization and rate-splitting multiple access communication: A Pareto optimization framework," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1496–1515, May 2023.

[A15] R. Huang, V. W. S. Wong, and R. Schober, "Rate-splitting for intelligent reflecting surface-aided multiuser VR streaming," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1516–1535, May 2023.

[A16] N. Q. Hieu, D. N. Nguyen, D. T. Hoang, and E. Dutkiewicz, "When virtual reality meets rate splitting multiple access: A joint communication and computation approach," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1536–1548, May 2023.

[A17] P. Chen, H. Liu, Y. Ye, L. Yang, K. J. Kim, and T. A. Tsiftsis, "Rate-splitting multiple access aided mobile edge computing with randomly deployed users," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1549–1565, May 2023.

[A18] R.-J. Reifert et al., "Rate-splitting and common message decoding in hybrid cloud/mobile edge computing networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 5, pp. 1566–1583, May 2023.

Bruno Clerckx (Fellow, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from the Université Catholique de Louvain, Belgium, and the D.Sc. degree from Imperial College London, London, U.K. He is currently a Professor, the Head of the Wireless Communications and Signal Processing Laboratory, and the Deputy Head of the Communications and Signal Processing Group, Department of Electrical and Electronic Engineering, Imperial College London. He is also the Chief Technology Officer (CTO) of Silicon Austria Labs (SAL), where he is responsible for all research areas of Austria's top research center for electronic-based systems. He has authored two books on MIMO wireless communications and MIMO wireless networks, 250 peer-reviewed international research articles, and 150 standards contributions. He is the inventor of 80 issued or pending patents among which 15 have been adopted in the specifications of 4G standards and are used by billions of devices worldwide. His research interests include wireless communications and signal processing for wireless networks. He is a fellow of IET and the IEEE Communications Society Distinguished Lecturer, from 2021 to 2022. He received the prestigious Blondel Medal 2021 from France for exceptional work contributing to the progress of science and electrical and electronic industries, the 2021 Adolphe Wetrems Prize in mathematical and physical sciences from the Royal Academy of Belgium, multiple awards from Samsung, the IEEE Best Student Paper Award, and the European Association for Signal Processing (EURASIP) Best Paper Award in 2022. He has served as an Editor or a Guest Editor for IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON SIGNAL PROCESSING, the *EURASIP Journal on Wireless Communications and Networking*, IEEE ACCESS, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING, the PROCEEDINGS OF THE IEEE, and the IEEE OPEN JOURNAL OF THE COMMUNICATIONS SOCIETY. He was an Editor of the "3GPP LTE-Advanced Standard Technical Report on CoMP."

Yijie Mao (Member, IEEE) received the B.Eng. degree from the Beijing University of Posts and Telecommunications, Beijing, China, the B.Eng. degree (Hons.) from the Queen Mary University of London, London, U.K., in 2014, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, China, in 2018. From 2018 to 2019, she was a Post-Doctoral Research Fellow at The University of Hong Kong. From 2019 to 2021, she was a Post-Doctoral Research Associate with the Communications and Signal Processing Group, Department of the Electrical and Electronic Engineering, Imperial College London, London. She is currently an Assistant Professor with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China. Her research interests include design of future wireless communications and artificial intelligence-empowered wireless networks. She has been a technical program committee member of many symposium on wireless communication for several leading international IEEE conferences. She was a recipient of the Best Paper Award of *EURASIP Journal on Wireless Communications and Networking* in 2022 and an Exemplary Reviewer of IEEE TRANSACTIONS ON COMMUNICATIONS in 2021. She has been the Vice-Chair of IEEE ComSoc WTC SIG on Rate-Splitting Multiple Access (RSMA) and the Workshop Co-Chair of IEEE ICC from 2020 to 2022, IEEE WCNC from 2021 to 2022, IEEE PIMRC from 2020 to 2022, and IEEE SECON 2022. She is currently serving as a Guest Editor for Special Issues of IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS and IEEE OPEN JOURNAL OF THE COMMUNICATIONS SOCIETY.

Eduard A. Jorswieck (Fellow, IEEE) was the Head of the Chair of Communications Theory and a Full Professor at Technische Universität Dresden (TU Dresden), Germany, from 2008 to 2019. He is currently the Managing Director of the Institute of Communications Technology and the Head of the Chair of Information Theory and Communications Systems and a Full Professor with Technische Universität Braunschweig, Brunswick, Germany. He has coauthored some 160 journal articles, 15 book chapters, four monographs, and more than 300 conference papers. His research interests include communications. In 2006, he received the IEEE Signal Processing Society Best Paper Award. He has served on the editorial boards of IEEE TRANSACTIONS ON SIGNAL PROCESSING, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE SIGNAL PROCESSING LETTERS, and IEEE TRANSACTIONS ON INFORMATION FORENSICS AND SECURITY. Since 2017, he serves as the Editor-in-Chief for the *EURASIP Journal on Wireless Communications and Networking* (Springer). He currently serves as an Editor for IEEE TRANSACTIONS ON COMMUNICATIONS.

Jinhong Yuan (Fellow, IEEE) is currently a Professor and the Head of the Telecommunication Group, School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, Australia. He has published two books, five book chapters, more than 300 papers in telecommunications journals and conference proceedings, and 50 industrial reports. He is a Co-Inventor of one patent on MIMO systems and four patents on low-density-parity-check codes. He has coauthored four best paper awards and one best poster award, including the Best Paper Award from the IEEE International Symposium on Wireless Communications Systems, Trondheim, Norway, in 2007, the IEEE Wireless Communications and Networking Conference, Cancun, Mexico, in 2011, and the IEEE International Conference on Communications, Kansas, MO, USA, in 2018. His current research interests include error control coding and information theory, communication theory, and wireless communications. He served as the IEEE NSW Chapter Chair for Joint Communications/Signal Processions/Ocean Engineering Chapter from 2011 to 2014 and an Associate Editor for IEEE TRANSACTIONS ON COMMUNICATIONS from 2012 to 2017. He is currently serving as an Associate Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and IEEE TRANSACTIONS ON COMMUNICATIONS.

David J. Love (Fellow, IEEE) is currently the Nick Trbovich Professor of electrical and computer engineering with Purdue University. He holds 32 issued U.S. patents. His research interests include design and analysis of broadband wireless communication systems, beyond 5G wireless systems, multiple-input multiple-output (MIMO) communications, millimeter wave wireless, software-defined radios and wireless networks, coding theory, and MIMO array processing. Since 2022, he has been a fellow of the American Association for the Advancement of Science (AAAS). Along with his coauthors, he won best paper awards from the IEEE Communications Society (2016 Stephen O. Rice Prize and 2020 Fred Ellersick Prize), the IEEE Signal Processing Society (2015 IEEE Signal Processing Society Best Paper Award), and the IEEE Vehicular Technology Society (2010 Jack Neubauer Memorial Award). He served as a Senior Editor for *IEEE Signal Processing Magazine*, an Editor for IEEE TRANSACTIONS ON COMMUNICATIONS, an Associate Editor for IEEE TRANSACTIONS ON SIGNAL PROCESSING, and a Guest Editor for Special Issues of IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS and the *EURASIP Journal on Wireless Communications and Networking*.

Elza Erkip (Fellow, IEEE) received the B.S. degree in electrical and electronics engineering from Middle East Technical University, Ankara, Turkey, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, USA.

She is currently an Institute Professor with the Department of Electrical and Computer Engineering, New York University Tandon School of Engineering. Her research interests include information theory, communication theory, and wireless communications. She was a member of the Board of Governors of the IEEE Information Theory Society from 2012 to 2020, where she was the President in 2018. She was a Distinguished Lecturer of the IEEE Information Theory Society from 2013 to 2014. She is a member of the Science Academy of Turkey. She received the NSF CAREER Award in 2001, the IEEE Communications Society WICE Outstanding Achievement Award in 2016, the IEEE Communications Society Communication Theory Technical Committee (CTTC) Technical Achievement Award in 2018, and the IEEE Communications Society Edwin Howard Armstrong Achievement Award in 2021. She was the Padovani Lecturer of the IEEE Information Theory Society in 2022. Her paper awards include the IEEE Communications Society Stephen O. Rice Paper Prize in 2004, the IEEE Communications Society Award for Advances in Communication in 2013, and the IEEE Communications Society Best Tutorial Paper Award in 2019.

Dusit Niyato (Fellow, IEEE) received the B.Eng. degree from the King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand, in 1999, and the Ph.D. degree in electrical and computer engineering from the University of Manitoba, Canada, in 2008. He is currently the President's Chair Professor with the School of Computer Science and Engineering, Nanyang Technological University, Singapore. His research interests include sustainability, edge intelligence, decentralized machine learning, and incentive mechanism design.