Digital Object Identifier 10.1109/OJAP.2024.3434008

Guest Editorial Special Section on Advanced Beam-Forming Antennas for Beyond 5G and 6G

I. INTRODUCTION

BEYOND 5G and 6G technologies mark a pivotal evolution in the telecommunications landscape. They are not only anticipated to deliver unprecedented speed and capacity but also to serve as critical enablers for a host of emerging technologies and applications, including joint communications and sensing, autonomous driving, augmented reality (AR), virtual reality (VR), and the burgeoning Internet of Things (IoT) [1], [2], [3]. As we transition into this new era, the expectations for system performance, reliability, and versatility are higher than ever before.

Beam-forming antennas, which allow for the intelligent and efficient management of signal beams, is essential for maximizing the system performance and reliability [4], [5]. It dynamically directs signal beams towards specific users or devices, thereby enhancing signal strength, reducing interference, and improving overall system efficiency. It is one of the key enabler for these next-generation systems. However, the development and deployment of beam-forming technologies are not without their challenges.

One pressing issue is cost reduction. The complicated hardware and complex algorithms required for effective beam-forming can be prohibitively expensive, especially as networks scale to accommodate millions of connected devices. Innovative approaches and new technologies are needed to develop cost-effective solutions that do not compromise on performance or reliability.

Another significant challenge is improving antenna flexibility. Next-generation systems must be able to adapt to rapidly changing environments and user demands. This requires antennas that are not only highly efficient but also extremely versatile. Reconfigurable antennas can dynamically adjust their properties to maintain optimal performance under varying conditions, ensuring seamless connectivity and superior user experiences.

Furthermore, with the deployment of large antenna arrays, the complexity of the system increases exponentially. Managing these large arrays involves intricate analysis and prediction to ensure that they function optimally. Fast and accurate prediction algorithms are crucial for real-time adjustments and performance tuning, helping to prevent issues before they affect the user experience. Advanced machine learning techniques and artificial intelligence (AI) are expected to play a pivotal role in enhancing these predictive capabilities, enabling systems to self-optimize and self-heal.

In this special section, we delve deeply into the advancements and developments in beam-forming technologies for beyond 5G and 6G. We explore the innovative solutions being developed to overcome current limitations and meet the challenges head-on. These include novel cost-reduction designs, advancements for enhanced antenna flexibility, and innovative analysis and prediction methods. By addressing these challenges, we can pave the way for future high-data-rate, high-capacity wireless systems, ensuring they are not only powerful but also accessible and efficient.

II. CONTRIBUTIONS

This special section features 11 peer-reviewed papers contributed by esteemed authors from various academic institutions across the globe. These contributors showcase the latest research on a broad spectrum of beam-forming antenna technologies applicable to beyond 5G and 6G systems. The contributions are organized into five categories based on their primary focus and the specific antenna technologies discussed. Table 1 lists these papers, including their authors and the main topics covered. The five categories of this collection and the corresponding papers are summarized as follows.

A. ADVANCED BEAM SCANNING

This category highlights the evolution of low-cost beam scanning technologies with broadened beam ranges and enhanced independent multi-beamforming capabilities.

Li et al. presented an exhaustive literature review on wide-angle beam scanning (WABS) phased array antennas [A1]. The paper focused on cost-effective solutions for next-generation wireless systems, addressing significant challenges such as element pattern beamwidth, array mutual coupling, and grating lobes. The discussion extends to the development of low-cost beam scanning technologies using a Generalized Joint Coupler (GJC) matrix, providing a forward-looking perspective on potential advancements in WABS technology.

Xu et al. introduced an innovative compact analog beamforming network based on the GJC matrix [A2]. This

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TABLE 1. List of papers in this special section.

Seq.	Authors	Key topic
A1	M. Li *et al.*	Wide-angle beam scanning
A2	Y. Xu *et al.*	Analog multi-beamforming
A3	Y.-X. Xie *et al.*	3D printed UWB metalens
A4	W.-Q. Deng *et al.*	Deep-learning assisted wideband metalens
A5	F. Mesa *et al.*	Physical optics lens
A6	M. Pubill-Font *et al.*	Ray-tracing dielectric dome
A7	S. Komeylian *et al.*	3D hybrid array
A8	S. Li *et al.*	Dual-pol beam switching
A9	S. Kim *et al.*	Series feed beam scanning
A10	L. Zhang *et al.*	Dual-beam filtering
A11	J.-E. Zhang *et al.*	Wideband mmWave DRA

design allowed for flexible beam angles with controlled low sidelobes. The successfully demonstrated prototypes achieved independent direction control of multiple beams through an engineered feeding network, maintaining sidelobe levels around −15 dB for all beams.

B. LENS ANTENNA

Lens antennas present a promising solution for beyond 5G and 6G systems, where high gains are necessary to compensate for significant propagation losses especially at high frequencies. Their ability to steer beams cost-effectively and straightforwardly makes them particularly attractive for these applications.

Xie et al. introduced an innovative design using ultra-wideband achromatic metalens antennas through three-dimensional (3D) printing technology [A3]. This work combines cost-efficiency with high performance, featuring a convex-like and a concave-like lens structure. It achieved an ultra-wide operational bandwidth, with a 3-dB gain bandwidth ranging from 50 to 102 GHz (2.04:1 bandwidth ratio). The design reaches a peak gain of 23.27 dBi, and the sidelobe levels are maintained below −20 dB.

Deng et al. effectively integrated deep learning with traditional optimization techniques to enhance both the transmission performance and scalability of metalens designs [A4]. Their innovative work introduced a multi- frequency phase matching concept that employs a synergistic combination of particle swarm optimization (PSO) and deep learning methodologies. This approach facilitated rapid and precise multi-frequency phase compensation, substantially optimizing antenna performance. The developed prototype metalens demonstrated its efficacy by achieving circular polarization (CP) with a 1-dB bandwidth ranging from 78 to 107 GHz.

C. ARRAY MODELING AND ANALYSIS

This category explores the challenges of analyzing large-scale arrays/lens efficiently and accurately, essential for 5G and beyond communication systems.

Mesa et al. presented an effective approach using physical optics (PO) method for planar graded-index and geodesic lens antennas [A5]. This method enabled efficient calculation of directivity and gain, while also taking material losses into account. The authors offered explicit formulas for calculating the radiation electric fields from the lens' aperture fields. By integrating ray tracing techniques, this approach is shown to be both computationally efficient and accurate, yielding significant reductions in both time and memory usage when compared to conventional HFSS simulations.

Pubill-Font et al. introduced an interesting ray-tracing model to evaluate the radiation characteristics of two- dimensional multilayer dielectric dome antennas [A6]. This model accounted for reflection and absorption losses and acted as a valuable initial step in the design of 3D lenses and domes for 5G/6G communications. This method dramatically decreased computational requirements, reducing simulation time by about 150 times compared to the COMSOL simulator, yet still preserving result accuracy.

Komeylian and Paolini focused on novel methods for identifying faulty elements in 3D hybrid antenna arrays, which implemented three different optimization models suited for arrays containing low, medium, and high percentages of non-radiating elements [A7]. This technique improved the estimation of direction-of-arrival (DoA), even with a high prevalence of faulty elements, and is supported by numerical results that demonstrate significant enhancements in performance.

D. BEAM RECONFIGURABLE ANTENNAS

Reconfigurable antenna technology is essential for adapting to dynamic environments and enhancing communication system performance in complex environment. This subsection highlights the advancements in beam switching technologies that contribute to this adaptability.

Li et al. developed a dual-polarization beam switching antenna featuring a compact integrated configuration [A8]. The horizontal polarization was achieved using a wheel-shaped radiating element, capable of reconfiguring to produce five beam patterns, including directional and omni-directional beams. Vertical polarization was enabled by a vertically placed center monopole accompanied by four reflectors, allowing for nine different beam states. This antenna supported extensive beam switching capabilities, ensuring good impedance matching and polarization isolation, thereby significantly enhancing system capacity and flexibility.

Kim et al. presented a center-fed beam steerable array utilizing a series feed configuration that maintains a wide operating bandwidth [A9]. The design incorporated innovative impedance transforming techniques to address the typical bandwidth reduction associated with increased antenna elements. The array was equipped with voltage- controlled phase shifters, facilitating easy control and enabling a beam scanning range of $\pm 60^\circ$. Notably, it exhibited a gain variation of less than 2 dB, an impedance matching bandwidth of 20% and minimal beam squint of $\pm 2^{\circ}$ over 200 MHz at a central frequency of 3.5 GHz.

E. OTHER INNOVATIVE FUNCTIONALITIES

In addition to the previous antenna technologies discussed, other innovative functionalities such as frequency regulation are crucial for optimizing antenna operation. Filtering technology plays a significant role in this context, and wideband capabilities that support various mmWave bands are particularly promising to further exploit the bandwidth usage for beyond 5G and 6G systems.

Zhang et al. introduced a dual-beam filtering patch antenna featuring a novel symmetrical π-shaped structure that merges two resonant modes [A10]. This design incorporates a cross-shaped metal strip printed on the patch resonator, which enhances the antenna's frequency selectivity and expands its bandwidth. The fabricated antenna achieved a 13% impedance bandwidth and a substantial 15-dB stopband at 2.14 times the center frequency. In addition, it realized a 20- dB roll-off coefficient, making it highly effective in filtering out-of-band signals.

Zhang et al. developed a broadband substrate integrated dielectric resonant antenna (SIDRA) that covers four mmWave bands (n257, n258, n260, and n261), ranging from 24.25 to 43.5 GHz [A11]. This antenna employs a novel multi-layer configuration that combines multiple resonant modes, enabling a wide bandwidth suitable for millimeter-wave (mmWave) systems. It displayed stable broadside beam patterns across the entire bandwidth. Moreover, the 1×4 SIDRA array demonstrated effective beam-scanning capabilities within the mmWave bands, highlighting its potential for future telecommunications infrastructure.

III. CONCLUSION

As we navigate the challenges of beam-forming antennas for beyond 5G and 6G systems, the research detailed here offers innovative solutions and methodologies that push the technology advancements. The collection of papers contributes to the field, demonstrating the potential of advanced beam-forming antennas/arrays to enhance system performance, reliability, and flexibility. From innovative approaches in lens and reconfigurable antennas to comprehensive array modeling and analysis, these studies provide a roadmap for overcoming the inherent challenges of next-generation systems. Notably, the integration of new materials, computational techniques, and machine learning into antenna design and beam-forming heralds a new era of efficiency and adaptability.

APPENDIX: RELATED ARTICLES

[A1] M. Li, S.-L. Chen, Y. Liu, and Y. J. Guo, "Wide-angle beam scanning phased array antennas: A review," *IEEE Open J. Antennas Propag.*, vol. 4, pp. 695–712, 2023, doi: 10.1109/OJAP.2023.3296636.

[A2] Y. Xu, H. Zhu, and Y. J. Guo, "Compact multi-beamforming networks based on generalized joined coupler matrix with flexible beam angles and low sidelobe levels," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 810–822, Aug. 2024, doi: 10.1109/OJAP.2023.3336764.

[A3] Y.-X. Xie, G.-B. Wu, W.-Q. Deng, S.-Y. Zhu, and C. H. Chan, "A 3-D Printed ultra-wideband achromatic metalens antenna," *IEEE Open J. Antennas Propag.*, vol. 4, pp. 713-723, 2023, doi: 10.1109/OJAP.2023.3295834.

[A4] W.-Q. Deng, H. Zhu, Y.-X. Xie, Z. Xu, and S.-Y. Zhu, "Design and optimization of an ultra-wideband millimeter-wave circularly polarized metalens antenna with deep learning method," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 823–832, Aug. 2024, doi: 10.1109/OJAP.2024.3367824.

[A5] F. Mesa, M. Chen, P. Castillo-Tapia, and O. Quevedo-Teruel, "Physical optics applied to parallel-plate lens antennas," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 833–844, Aug. 2024, doi: 10.1109/OJAP.2023.3347347.

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[A7] S. Komeylian and C. Paolini, "Modeling of the fault detection problem for a 3D hybrid antenna array: Analysis and evaluation," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 855–868, Aug. 2024, doi: 10.1109/OJAP.2024.3378116.

[A8] S. Li, M. Chen, Z. Li, J. Chen, and J. Wang, "A WLAN dual-polarized beam-reconfigurable antenna," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 869–878, Aug. 2024, doi: 10.1109/OJAP.2024.3373913.

[A9] S. Kim, H. Park, and B.-W. Min, "A center-fed beam-steerable series antenna array with a wide matching bandwidth," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 879–887, Aug. 2024, doi: 10.1109/OJAP.2024.3366809.

[A10] L. Zhang, T. Ni, J. Shi, G. Liu, and K. Xu, "A dual-beam filtering antenna based on dual-mode patch loaded with π-shaped vias," *IEEE Open J. Antennas Propag.*, vol. 5, no. 4, pp. 888–894, Aug. 2024, doi: 10.1109/OJAP.2024.3353810.

[A11] J.-E. Zhang, Q. Zhang, W. Qin, W.-W. Yang, and J.-X. Chen, "Compact and broadband substrate integrated dielectric resonator antenna suitable for 5G millimeter-wave communications," *IEEE Open J. Antennas Propag.*, vol. 4, pp. 982-989, 2023, doi: 10.1109/OJAP.2023.3319631.

ACKNOWLEDGMENT

In closing, the Guest Editors express their gratitude to the authors and reviewers for their dedication, which has ensured the timely completion of this section. We hope that the research presented here will inspire new applications and advancements in beam-forming antenna technologies for Beyond 5G and 6G networks, exploring uncharted opportunities. Special thanks are due to Prof. Shen, the Editor- in-Chief of the IEEE OPEN JOURNAL OF ANTENNAS AND PROPAGATION, Dr. Zhu, the Senior Editor, and Sunny Tse, the Administrative Editor, for their invaluable support in making this Special Section possible.

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SHU-LIN CHEN, *Guest Editor*
Global Big Data Technologies Centre
University of Technology Sydney
Ultimo, NSW 2007, Australia
E-mail: shulin.chen@uts.edu.au

Y. JAY GUO, *Guest Editor*
Global Big Data Technologies Centre
University of Technology Sydney
Ultimo, NSW 2007, Australia
E-mail: jay.guo@uts.edu.au

DONGZE ZHENG, *Guest Editor*
State Key Laboratory of Millimeter Waves
Southeast University
Nanjing 210096, Jiangsu, China
E-mail: donzheng@seu.edu.cn

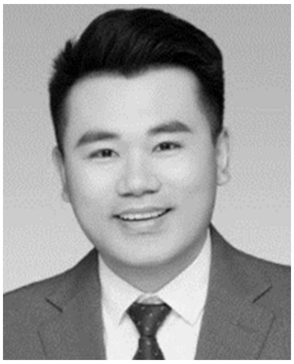
KE WU, *Guest Editor*
Poly-Grames Research Center
Polytechnique Montréal
Montreal, QC H3T 1J4, Canada
E-mail: ke.wu@polymtl.ca

GENG-BO WU, *Guest Editor*
State Key Laboratory of Terahertz and Millimeter Waves
City University of Hong Kong
Hong Kong, SAR, China
E-mail: bogwu2@cityu.edu.hk

CHI HOU CHAN, *Guest Editor*
State Key Laboratory of Terahertz and Millimeter Waves
City University of Hong Kong
Hong Kong, SAR, China
E-mail: eechic@cityu.edu.hk

SHU-LIN CHEN (Member, IEEE) was born in Hubei, China. He received the B.S. degree in electrical engineering from Fuzhou University, China, in 2012, the M.S. degree in electromagnetic field and microwave technology from Xiamen University, China, in 2015, and the Ph.D. degree in engineering from the University of Technology Sydney (UTS), Australia, in 2019.

From April to July 2019, he was a Research Associate with the State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong. From 2019 to 2022, he was a Postdoctoral Researcher with the Global Big Data Technologies Centre, UTS, where he is currently appointed as a Lecturer. His research interests include reconfigurable antennas, leaky-wave antennas, intelligent metasurfaces, and array synthesis. He received the Outstanding Master's Thesis of Fujian Province in 2015. He was a co-recipient for a number of prestigious conference paper awards, including the Honorable Mention Award in 2017 IEEE AP-S/URSI, the Best Paper Award Finalists in 2017 ISAP, the Best Paper Award in 2018 ISAPE, the First Prize of Student Paper in 2021 ACES, and the Best Young Professional Award in 2022 ISAP. He was awarded the TICRA-EurAAP Travel Grant for the 2022 EuCAP and the 2022 IEEE Antennas and Propagation Society Fellowship. He is serving as an Associate Editor for the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS–II: EXPRESS BRIEFS. He is also serving as a Lead Guest Editor of the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, Special Cluster on "Intelligent and Highly Efficient Antennas/Metasurfaces for 6G" and IEEE OPEN JOURNAL OF ANTENNAS AND PROPAGATION, Special Section on "Advanced Beamforming Antennas for Beyond 5G and 6G."



DONGZE ZHENG (Member, IEEE) was born in Bozhou, Anhui, China, in 1993. He received the B.S. degree from Anhui University, Hefei, China, in 2014, the M.S. degree from the South China University of Technology, Guangzhou, China, in 2017, and the Ph.D. degree from the Polytechnique Montréal (University of Montréal), Montreal, Canada, in 2022.

He was a Postdoctoral Research Fellow with the State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong, Hong Kong, SAR, from March 2022 to March 2023. He is currently an Associate Professor with the State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing, China. He was an Outstanding Graduate, when he graduated from Anhui University in 2014. His master's thesis was selected as one of the excellent theses of the SCUT in 2017. His research interests include leaky-wave structures and antennas, frequency-scanning radar sensing/imaging systems, slow-wave structures/artificial transmission lines, and phased arrays.

Dr. Zheng was the recipient of the "Honorable Mention" Award for the Student Paper Competition at the IEEE APS/URSI Conference, Montreal, Canada, in 2020. His Ph.D. thesis received the Annual Best Thesis Award (Special Mention) of the Polytechnique Montréal (University of Montréal) in 2021. In addition, he was selected for the "Ph.D. Sponsorship Initiative" Program at the IEEE International Microwave Symposium Conference, Boston, USA, in 2019. He served as a Session Chair/TPC Member in several conferences, including IEEE ICMMT 2023, ACES 2023, and IMWS-AMP 2023, and also served as a Guest Editor for the IEEE OPEN JOURNAL OF ANTENNAS AND PROPAGATION in 2023. He is currently serving as a Review Editor for *Frontiers in Antennas and Propagation*, a member of the Young Editorial Board of Electromagnetic Science, and an Affiliate Member of IEEE MTT- S 4th Technical Committee "Microwave Passive Components and Transmission Line Structures."

GENGBO WU (Member, IEEE) received the B.Eng. and M.Sc. degrees from the University of Electronic Science and Technology of China, Chengdu, China, in 2015 and 2018, respectively, and the Ph.D. degree from the City University of Hong Kong (CityU), Hong Kong, in 2021.

From 2021 to 2023, he was a Postdoctoral Research Fellow with the State Key Laboratory of Terahertz and Millimeter Waves (SKLTMW), CityU, where he is currently an Assistant Professor with the Department of Electrical Engineering. He is also a member of SKLTMW, CityU. His research interests include millimeter-wave/THz antennas, reconfigurable intelligent surfaces, spatiotemporal modulation technology, integrated sensing, and communications.

Dr. Wu was the recipient of Gold Model with Congratulations of the Jury and Gold Model in the 49th and 48th International Exhibition of Inventions Geneva in 2024 and 2023, the IEEE Antennas and Propagation Society Fellowship in 2022, the Best Student Paper Award Finalists in the 14th European Conference on Antennas and Propagation in 2020, the Honorable Mention Award in IEEE AP-S/URSI in 2020, and the Best Student Presenter Award in the 2019 EE Student Research Symposium, CityU. He has been serving as a Committee Member of the IEEE Hong Kong AP/MTT Joint Chapter since 2022.

Y. JAY GUO (Fellow, IEEE) received the bachelor's and master's degrees from Xidian University, China, in 1982 and 1984, respectively, and the Ph.D. degree from Xian Jiaotong University, China, in 1987.

He is a Distinguished Professor and the Director of the Global Big Data Technologies Centre, University of Technology Sydney (UTS), Australia. He is the Founding Technical Director of the New South Wales Connectivity Innovation Network. Prior to joining UTS in 2014, he was the Director of CSIRO for over nine years. Before joining CSIRO, he held various senior technology leadership positions with Fujitsu, Siemens, and NEC in the U.K. He has published five books and over 700 research papers, including over 300 IEEE TRANSACTIONS papers, and he holds 26 international patents. His research interests include antennas, mm-wave and THz communications and sensing systems as well as big data technologies. His research interest includes multibeam antenna systems, re-configurable antennas and metasurfaces, and joined communications and sensing for 6G.

Dr. Guo received the prestigious IEEE APS Sergei A. Schelkunoff Transactions Paper Prize Award in 2023. He has won a number of the most prestigious Australian national awards, including the Engineering Excellence Awards in 2007 and 2012, and the CSIRO Chairman's Medal in 2007 and 2012. He was named one of the most influential engineers in Australia in 2014 and 2015, and Australia's Research Field Leader in Electromagnetism by the Australian Research Report for three consecutive years since 2020. Together with his students and postdoctorals, he has won numerous best paper awards. He has chaired numerous international conferences and served as a guest editor for a number of IEEE publications. He was the Chair of International Steering Committee, International Symposium on Antennas and Propagation from 2019 to 2021. He has been the International Advisory Committee Chair of IEEE VTC2017, the General Chair of ISAP2022, ISAP2015, iWAT2014, and WPMC'2014, and the TPC Chair of 2010 IEEE WCNC, and 2012 and 2007 IEEE ISCIT. He served as a Guest Editor of special issues on "Low-Cost Wide-Angle Beam Scanning Antennas, Antennas for Satellite Communications," and "Antennas and Propagation Aspects of 60-90 GHz Wireless Communications," all in IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, Special Issue on "Communications Challenges and Dynamics for Unmanned Autonomous Vehicles," IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, and Special Issue on "5G for Mission Critical Machine Communications," *IEEE Network Magazine*. He is a Fellow of the Australian Academy of Engineering and Technology. He was a member of the College of Experts of Australian Research Council from 2016 to 2018.

KE WU (Fellow, IEEE) received the B.Sc. degree (Hons.) in radio engineering from the Nanjing Institute of Technology (currently Southeast University), Nanjing, China, in 1982, the D.E.A. degree (Hons.) in optics, optoelectronics, and microwave engineering from the Institut National Polytechnique de Grenoble, in 1984, and the Ph.D. degree (Hons.) in optics, optoelectronics, and microwave engineering from the University of Grenoble, Grenoble, France, in 1987.

He was the Founding Director of the Center for Radio frequency Electronics Research of Quebec (Regroupement strate'gique of FRQNT) and the Canada Research Chair of RF and Millimeter-Wave Engineering. He is currently a Professor of Electrical Engineering and the Industrial Research Chair of Future Wireless Technologies with the Polytechnique Montréal (University of Montreal), where he is the Director of the Poly-Grames Research Center. He has authored or co-authored over 1500 referred articles and numerous books/book chapters and filed over 90 patents. His current research interests involve substrate integration technologies, antenna arrays, field theory and joint field/circuit modeling, ultrafast guided-wave electronics, wireless power transfer and harvesting, microwave photonics, and MHz-through-THz technologies and transceivers, including RFICs/MMICs for joint radar/communication architectures, innovative multifunction wireless systems, and biomedical applications.

Dr. Wu was a recipient of many awards and prizes, including the inaugural IEEE MTT-S Outstanding Young Engineer Award, the 2004 Fessenden Medal of the IEEE Canada, the 2009 Thomas W. Eadie Medal of the Royal Society of Canada, the Queen Elizabeth II Diamond Jubilee Medal in 2013, the 2013 FCCP Education Foundation Award of Merit, the 2014 IEEE MTT-S Microwave Application Award, the 2014 Marie-Victorin Prize (Prix du Quebec), the 2015 Prix d'Excellence en Recherche et Innovation of Polytechnique Montréal, the 2015 IEEE Montreal Section Gold Medal of Achievement, the 2019 IEEE MTT-S Microwave Prize, the 2021 EIC Julian C. Smith Medal, the 2022 IEEE MTT-S Outstanding Educator Award, and the 2022 IEEE AP-S John Kraus Antenna Award. He has held key positions in and has served on various panels and international committees, including the Chair of technical program committees, international steering committees, and international conferences/symposia. In particular, he was the General Chair of the 2012 IEEE Microwave Theory and Techniques (IEEE MTT-S) International Microwave Symposium and the TPC Co-Chair of the 2020 IEEE International Symposium on Antennas and Propagation. He has served on the editorial/review boards for many technical journals, transactions, proceedings, and letters as well as scientific encyclopedia, including an editor, a track editor, and a guest editor. He was the Chair of the Joint IEEE Montreal Chapters of MTT-S/AP-S/LEOS and then the restructured IEEE MTT-S Montreal Chapter, Canada. He has served the IEEE MTT-S Administrative Committee (AdCom) as the Chair for the IEEE MTT-S Transnational Committee, the Member and Geographic Activities Committee, Technical Coordinating Committee, and the 2016 IEEE MTT-S President among many other AdCom functions. He is currently the Chair of the IEEE MTT-S Inter-Society Committee. He was a Distinguished Microwave Lecturer of the IEEE MTT-S from 2009 to 2011. He served the European Microwave Association as the Inaugural Representative of North America in its General Assembly. He is a member of the Electromagnetics Academy, URSI, and IEEE-Eta Kappa Nu (IEEE- HKN). He is a Fellow of the Canadian Academy of Engineering, the Academy of Science of the Royal Society of Canada, and the German National Academy of Science and Engineering (acatech).

CHI HOU CHAN (Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from The Ohio State University, Columbus, OH, USA, in 1981 and 1982, respectively, and the Ph.D. degree in electrical engineering from the University of Illinois at Urbana–Champaign (UIUC), IL, USA, in 1987.

From 1987 to 1989, he was a Visiting Assistant Professor with the Department of Electrical and Computer Engineering, UIUC. He joined the Department of Electrical Engineering, University of Washington, Seattle, WA, USA, in 1989, and was promoted to an Associate Professor with tenure in 1993. In 1996, he joined the Department of Electronic Engineering (currently Electrical Engineering), City University of Hong Kong (CityU) as a Professor and was promoted to the Chair Professor of Electronic Engineering in 1998. From 1998 to 2009, he was a first Associate Dean and then the Dean of the College of Science and Engineering, CityU. He also served as Acting Provost of the University from July 2009 to September 2010 and again from December 2022 to May 2023. He is currently the Director of the State Key Laboratory of Terahertz and Millimeter Waves (City University of Hong Kong) and the Vice President (Community Engagement). His current research interests include millimeter-wave and terahertz antennas, integrated circuits, and imaging.

Prof. Chan was be-stowed with the IEEE Antennas and Propagation Society Harrington-Mittra Computational Electromagnetics Award and the Distinguished Alumni Award from ECE, UIUC in 2019. He was elected an IEEE Fellow in 2002, with the citation of "For Contributions to Computational Electromagnetics."