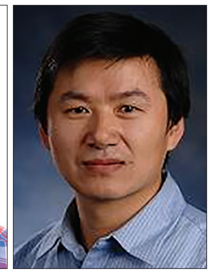
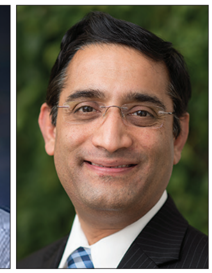
Recent Advances in Optical Wireless Communications for 6G, WLANs and Beyond

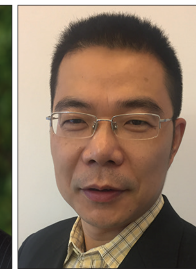

Yuanqiu Luo


Admela Jukan


Krishna M. Sivalingam


Xiaojun (Matt) Cao


Suresh Subramaniam


Gangxiang (Steven) Shen

Current changes of information creation, sensing, sharing, and consumption in our community, business, and industry have stimulated data traffic surge. Next generation communication networks are evolving with the goal of providing high data rate, stringent latency, and ubiquitous services. Optical wireless communication (OWC) systems are being actively developed with combined benefits from advanced optical and wireless technologies. With advantages, such as ultra-high bandwidth, long distance, and strong data privacy, optical wireless systems will become an essential building block of the future communication network infrastructure. OWC will play an important role in network operations for 6G, satellite communications, wireless LANs (WLAN), and beyond.

This Special Issue (SI) promotes applications of OWC in emerging networks and services. It presents the latest research endeavors, network design, as well as system implementation in the fields of terahertz communication, visible light communication, home networking, underwater communication, and low-earth orbit (LEO) satellite connectivity. These technical advances are promising in developing 6G, WiFi 8, and other network and service solutions. This SI also investigates theoretical and practical challenges to encourage a joint effort from both academia and industry. After a rigorous review process, eight articles have been accepted. They cover four major aspects within this field.

The first set of articles surveys the OWC technical challenges and advances. They provide a comprehensive status update on OWC by reviewing the most recent research efforts on physical layer evaluation, communication technology enhancement, and device design.

An article, "Optical and Terahertz Wireless Technologies: The Race to 6G Communications," by Shehata *et al.*, compares the key aspects of terahertz and OWC technologies. Specifications in IEEE Standards 802.15 are used as examples. Major differences on transceiver design, signal power, modulation format, transmission range, and user mobility are investigated. These differences lead to disparate system design principles. In the terahertz 6G system, its high throughput is enabled by spectrally efficient transmission techniques and advanced digital signal processing (DSP). The OWC 6G system throughput is mainly facilitated by the high transmitted signal power and advanced optics. Potential scenarios of integrating terahertz and OWC technologies for 6G communications are explored to take advantage of both areas.

Another article, "How Cooperative Communication Distinguishes in Wireless Optical Systems," by Liu *et al.*, investigates potential applications of cooperative communications from the radio domain in OWC. The proposed OWC system combines key technologies, such as heterogeneous cooperative transmission, asymmetrical constellation, elastic optical power distribution, and intelligent channel prediction. The OWC link loss due to atmospheric dynamics and environmental turbulence is compensated via the cooperative communication of optical and wireless media.

The third article in this set, "Optical Reconfigurable Intelligent Surfaces Aided Optical Wireless Communications: Opportunities, Challenges, and Trends," by Wang *et al.*, surveys recent advancements in optical reconfigurable intelligent surface (ORIS) devices. By changing the optical beam characteristics, such as direction, shape, amplitude, and phase, ORIS devices expand the applications of OWC systems. This article further discusses the ORIS aided OWC system structure, operation modes, and key functions. Potential solutions to free space optical (FSO) communication, underwater communication, and LEO satellite are also surveyed.

The second set includes two articles on the OWC indoor applications. They are joint work from academia and industry. One explores the next generation indoor short-range communication technology based on visible light communication (VLC). The other integrates WLAN and optical home networking to enable Gigabit home experience.

An article, "Terabit Indoor Laser-Based Wireless Communications: LiFi 2.0 for 6G," by Soltani *et al.*, introduces vertical cavity surface-emitting laser (VCSEL) technologies for 6G indoor communications. By employing infrared light and integrated VCSEL arrays, the indoor signal rate can reach multi-Gigabit. This new effort is called LiFi 2.0. It is different from LiFi 1.0, which relies on VLC and LED sources for signal transmission. The receiver of LiFi 2.0 features a design based on an "array of arrays" structure with small photodiodes. Standards and development status relevant to LiFi 2.0 are reviewed to illustrate OWC applications in 6G.

The other article in this set, "Wireless Access Technology in FTTR Next Generation Home Networks: An Overview," by Chang *et al.*, explores the OWC application in home networking. The fiber-to-the-room (FTTR) solution employs passive optical network technologies to connect rooms in a residential house. A WiFi access point is installed in each room to deliver multi-Gigabit data rates with consistent and ubiquitous quality of service. Candidate methods on WiFi channel allocation, WLAN management, and user roaming are discussed in detail. It presents a testbed and test results in the real home environment, demonstrating tradeoffs between the FTTR system performance and implementation complexity.

The third set of articles in our SI introduces advancements in OWC outdoor applications. They report industrial R&D efforts on OWC device innovation and system enhancement.

An article, "Free Space Optical Communication Systems for 6G: A Modular Transceiver Design," by Bekkali *et al.*, proposes an FSO transceiver design based on a modular concept. The key issue of signal degradation due to laser beam on-axis deviation is addressed by using multiple tracking and correction modulars. The electrical hardware and control software jointly steer the laser beam to hit the receiver lens accurately. The transceiver is tested in outdoor scenarios. It achieves 10 Gbps error-free wireless signal transmission in different weather conditions.

The other article in this set, "Toward Manageable Cost-Effective 5G C-RAN: Semi-Active Front-Haul by Multi-Carrier Pilot-Tone OAM and MWDM," by Zhang *et al.*, proposes an optical system for the wireless front-haul transport. The prototype performance is tested in a field trial of a top operator's network. The trial demonstrates an error-free 300-Gb/s real-time wireless front-haul transmission. The proposed system connects active antenna units (AAUs) and distributed units (DUs) up to 10 km apart in the wireless network front-haul. It meets the requirements of the centralized, collaborative, cloud, and clean radio access network (C-RAN) in 5G and beyond.

The last set addresses the OWC network design. It embodies the interdisciplinary endeavor of applying quantum research achievements in network research.

An article, "A Quantum-Behaved Heterogeneous Topology Optimization Model for Optical Wireless Communication Networks," by Zhang *et al.*, tackles the issue of OWC network topology design. It models the unstable OWC links and the weather impact by employing quantum behavior. The experimental results show that the OWC network topology can be optimized to achieve both network robustness and communication efficiency.

The Guest Editors thank all the authors for submitting their high-quality work, the anonymous reviewers for their insightful comments, and the Editor-in-Chief and IEEE WCM staff members for their steady support. Due to space limitations, many papers could not be published in this SI, but we anticipate reading them in other venues. We hope that the readers enjoy this SI.

Biographies

Yuanqiu Luo (yuanqiu.luo@futurewei.com) received her Ph.D. degree in Electrical Engineering from the New Jersey Institute of Technology, Newark. She is currently a Director of Optical Access Standards in Futurewei Technologies, USA. She has been heavily involved in the R&D effort of access networks for over 15 years. She is the Chair of IEEE 802.3dk Task Force. She was the chief editor of IEEE Standards 802.3cp and a clause editor of IEEE standards 802.1AS. She is an editor of ITU Recommendations G.987.3, G.9807.1, G.989.2, G.9802, G.9803, G.Sup66, G.9804.2, and G.988. Dr. Luo is a Senior Member of IEEE. She is a member of the IEEE ComSoc Educational Services Board (ESB), a member of the IEEE ComSoc Industry Outreach Board (IOB), and a technical editor of *IEEE Wireless Communications*. She serves as an IEEE ComSoc Distinguished Lecturer (term 2022–2023) and an ICC 2024 Workshops Co-Chair. She received the Best Paper Award from IEEE & OSA Journal of Lightwave Technology. She was a two-time recipient of the IEEE Standards Award (both 2011 and 2021). She was selected to the 2021 N^{2}Women: Stars in Computer Networking and Communications.

Admela Jukan (ajukan@me.com) is Chair Professor of Communication Networks at the Technische Universität Carolo-Wilhelmina zu Braunschweig (Brunswick), Germany. Prior to that post, she was research faculty at the Institut National de la Recherche Scientifique (INRS) and Georgia Tech (GaTech). She was a visiting scientist at Bell Labs, Holmdel, NJ, at University of Illinois at Urbana Champaign (UIUC) and MIT. She served as program Director in Computer and Networks System Research at the National Science Foundation (NSF) in Arlington, VA. Professor Jukan is a Fellow of the IEEE. She serves as Senior Editor in the *IEEE Journal of Selected Areas in Communications*. She is a co-Editor in Chief of the *Elsevier Journal on Optical Switching and Networking (OSN)*. She was an elected Chair of the IEEE Optical Network Technical Committee, ONTC. Admela Jukan received her Dr.tech. degree (summa cum laude) in Electrical and Computer Engineering from the Technische Universität Wien, her M.Sc. degree in Information Technologies from the Politecnico di Milano, Italy, and her Dipl. -Ing. degree from the Fakultet Elektrotehnike i Racunarstva (FER), in Zagreb, Croatia.

Krishna M. Sivalingam [F] (skrishnam@cse.iitm.ac.in) is the Gopalakrishnan Institute Chair Professor in the Department of CSE, IIT Madras, Chennai, INDIA, where he was also Head of the Department, from 2016 until 2019. Previously, he was a professor in the Dept. of CSEE at University of Maryland, Baltimore County, Maryland, USA from 2002 until 2007; with the School of EECS at Washington State University, Pullman, USA from 1997 until 2002; and with the University of North Carolina Greensboro, USA from 1994 until 1997. He has also conducted research at Lucent Technologies' Bell Labs in Murray Hill, NJ, and at AT&T Labs in Whippany, NJ. He received his Ph.D. and M.S. degrees in Computer Science from State University of New York at Buffalo, in 1994 and 1990, respectively; and his B.E. degree in Computer Science and Engineering, in 1988, from Anna University's College of Engineering Guindy, Chennai (Madras), India. While at SUNY Buffalo, he was a Presidential Fellow from 1988 to 1991.His research interests include wireless networks, network protocols, and performance evaluation. His work has been supported by several sources, including AFOSR, DST India, DOT India, IBM, NSF, Cisco, Intel, Tata Power Company, VMWare, and Laboratory for Telecommunication Sciences. He holds three patents in wireless networks and has published several research articles including more than eighty journal publications. He has co-edited a book on Next Generation Internet Technologies, in 2010; on Wireless Sensor Networks, in 2004; on optical WDM networks, in 2000 and 2004. He is serving or has served as a member of the Editorial Board for journals including *IEEE Networking Letters*, *ACM Wireless Networks Journal*, *IEEE Transactions on Mobile Computing*, and *Elsevier Optical Switching and Networking Journal*. He has served as Editor-in-Chief of *Springer Photonic Network Communications Journal* and *EAI Endorsed Transactions on Future Internet*. He is a Fellow of INAE and an ACM Distinguished Scientist.

Xiaojun (Matt) Cao (cao@gsu.edu) received his B.S. degree from Tsinghua University and M.S. degree from Chinese Academy of Sciences, in 1996 and 1999, respectively. In June 2004, he received his Ph.D. degree in Computer Science and Engineering from the State University of New York at Buffalo. Currently, he is a Professor at the Computer Science Department of Georgia State University. He and his group are working on modeling, analysis, protocols/algorithms design, as well as data processing for networks and cyber-physical systems. He was a distinguished lecturer of the IEEE ComSoc (2019–2020) and served as the chair of IEEE Comsoc ONTC. His research has been sponsored by the U.S. National Science Foundation (NSF), Centers for Disease Control and Prevention (CDC), IBM, and Cisco's University Research Program. He is a recipient of the NSF CAREER Award, 2006-2011.

Suresh Subramaniam [S'95, M'97, SM'07, F'15] (suresh@gwu.edu) is Vice Provost for Graduate and Postdoctoral Affairs and Professor of Electrical and Computer Engineering at the George Washington University, Washington DC, where he directs the Lab for Intelligent Networking and Computing. He received his Ph.D. degree in electrical engineering from the University of Washington, Seattle, in 1997. His research interests are in the architectural, algorithmic, and performance aspects of communication networks, with current emphasis on optical networks, cloud computing, data center networks, and IoT. He has published over 250 peer-reviewed papers in these areas. He is a co-editor of three books on optical networking. He has served in leadership positions for several top conferences, including IEEE ComSoc's flagship conferences of ICC, Globecom, and INFOCOM. He serves/has served on the editorial boards of seven journals including the *IEEE/ACM Transactions on Networking* and the *IEEE/Optica Journal of Optical Communications and Networking*. During 2012 and 2013, he served as the elected Chair of the IEEE Communications Society Optical Networking Technical Committee (ONTC). He has received multiple best paper awards, received the 2017 SEAS Distinguished Researcher Award from George Washington University, and the 2022 Outstanding Technical Achievement Award from ComSoc ONTC. He was an IEEE Distinguished Lecturer during 2018-2021. He is a Fellow of the AAIA.

Gangxiang Shen [SM] (shengx@suda.edu.cn) received his B.Eng. degree from Zhejiang University, China, his M.Sc. degree from Nanyang Technological University, Singapore, and his Ph.D. degree from the University of Alberta, Edmonton, AB, Canada, in 2006. He currently holds the position of Dean and Distinguished Professor at the School of Electronic and Information Engineering, Soochow University, Suzhou, China. Before joining Soochow University, he worked as a Lead Engineer with Ciena in Linthicum, MD, USA. He was also an Australian ARC Postdoctoral Fellow with the University of Melbourne, Melbourne, VIC, Australia. He has authored and coauthored more than 250 peer-reviewed technical papers. His research focuses on various areas, including spectrum-efficient optical networks, green optical networks, and integrated optical and wireless networks. He was the Lead Guest Editor of the *IEEE Journal on Selected Areas in Communications* Special Issue on Next-Generation Spectrum-Efficient and Elastic Optical Transport Networks, and the Guest Editor of the *IEEE Journal on Selected Areas in Communications* Special Issue on Energy-Efficiency in Optical Networks. He was an Associate Editor for the *IEEE/OSA Journal of Optical Communication and Networking*, and currently holds the position of Associate Editor for the IEEE/OSA *Journal of Lightwave Technology the IEEE Networking Letters*. He is also an Editorial Board Member of *Optical Switching and Networking and Photonic Network Communications*. He was the recipient of Young Researcher New Star Scientist Award, in 2010, Scopus Young Researcher Award Scheme in China, the Izaak Walton Killam Memorial Award from the University of Alberta, and the Canadian NSERC Industrial Research and Development Fellowship. He has also been consistently recognized as a Highly Cited Chinese Researcher by Elsevier, from 2014 to 2022. Moreover, he was honored as an elected IEEE ComSoc Distinguished Lecturer for the term 2018–2019, and served as a Member at Large of the IEEE ComSoc Strategic Planning Standing Committee, from 2018 to 2021. He is also an elected Fellow of OPTICA.