Optical Wireless in Space, 6G, and X-Haul Networks


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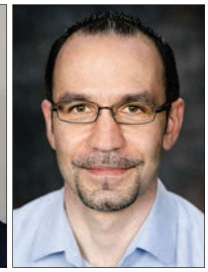
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Optical wireless communication (OWC), also called free-space optical communication, has recently evolved in many significant ways, and is now employed in a wide range of terrestrial and space applications. Examples include optical inter-satellite links for Low-Earth Orbit (LEO) satellite, airborne or terrestrial optical wireless links for backhaul/fronthaul networks, and indoor visible light communication that piggybacks wireless data transfer to solid-state lighting infrastructure. OWC offers the use of unlicensed spectrum, has much larger bandwidth than legacy radio frequency (RF) systems, and is naturally more secure with low probability-of-intercept. Continued innovations in OWC technologies have accelerated commercialization efforts across many emerging applications. However, as these optical wireless systems and components are becoming more common, new design challenges emerge in their integration to the mainstream wireless communication technologies.

Challenges arising from mobility and scarcity of line-of-sight (LoS) are among the most notable ones for OWC solutions. Since optical beams are highly directional, aligning transmitter and receiver platforms requires particular attention to properly tap into the benefits offered by OWC. Consideration of the environmental factors, such as atmospheric attenuation and ambient interference, on the OWC channel quality is necessary as well. OWC solutions, addressing these challenges by embodying hardware with efficient and appropriate form factor as well as smart algorithmic approaches to manage multitude of underlying resources, are needed to enable future 6G applications requiring gigabit-per-second wireless speeds.

This Feature Topic (FT) presents seven articles that offer coverage of the technological advancement and challenges of OWC in terms of system design as well as theoretical modeling aspects.

The article "Simultaneous Lightwave Information and Power Transfer in 6G Networks" by Vasilis K. Papanikolaou, Sotiris A. Tegos, Kapila W. S. Palitharathna, Panagiotis D. Diamantoulakis, Himal A. Suraweera, Mohammad-Ali Khalighi, and George K. Karagiannidis, demonstrates the simultaneous transfer of data, via OWC, and power, via harvesting of the carrier energy at the receiver. The ability to wirelessly deliver power in conjunction with data not only contributes to the sustainability of communication infrastructure for 6G and beyond, but also contributes to overcoming the digital divide by alleviating the burden on the power grid in under-connected communities. The authors provide a comprehensive study of this technology for a number of indoor and outdoor applications, identifying opportunities for immediate impact and future advancement.

The article "Free-Space Optical Communication Technologies for Next-Generation Cellular Wireless Communications" by Gihong Park, Vuong Mai, Hojae Lee, Sangrim Lee, and Hoon Kim, studies challenges in integrating OWC solutions to legacy cellular networks. The study points to an approach that advocates for using OWC for LoS links when the opportunity arises and resorting to RF bands for non-LoS situations. Attempting to get the best of both worlds, this approach offers very high speed communication via directional OWC channels during opportunities to set up LoS links and utilizes wide coverage of RF links otherwise.

The article "Pointing-and-Acquisition for Optical Wireless in 6G: From Algorithms to Performance Evaluation" by Hyung-Joo Moon, Chan-Byoung Chae, Kai-Kit Wong, and Mohamed-Slim Alouini, investigates novel pointing and acquisition architectures for aerial and non-terrestrial OWC links. The many benefits of the narrow beams achievable at optical frequencies, such as increased link margin and reduction of interference, brings about the challenge of rapid and on-demand establishment of the link in the first place. The authors demonstrate, via simulations, the advantage of having simultaneous RF and optical carriers active between the two nodes of interest. They show that angle-of-arrival information generated from the RF carrier can aid optical feedback loops to reduce acquisition time and increase robustness of the link in dynamic air-ground communication scenarios.

The article "Unraveling "Fiber in the Sky": Terabit Capacity Enabled by Coherent Optical Wireless" by Marco A. Fernandes, Gil M. Fernandes, Bruno T. Brand˜ao, Manuel M. Freitas, Nourdin Kaai, Bas van Der Wielen, John Reid, Daniele Raiteri, Paulo P. Monteiro, Fernando P. Guiomar, presents a 400-Gbps high-speed optical wireless communication experiment over a 1.8 km horizontal link. The prototype uses automatic power control and artificial neural network algorithm in its state-of-the-art coherent transceivers, showing the potential applications both for terrestrial and space communication scenarios.

The article "Centimeter-Level Indoor Visible Light Positioning" by Ran Zhu, Maxim Van den Abeele, Jona Beysens, Jie Yang, and Qing Wang, showcases a data-driven approach to improve indoor localization accuracy using visible light communication. The method processes collected positioning data via machine learning (ML) algorithms that can work on low-resource small embedded systems devices. As small as 1.7 cm positioning error is demonstrated by the design, demonstrating a large application potential for indoor settings where localization with high accuracy, such as items in a supermarket, is required.

The article "Single-Photon Counting Receivers for 6G Optical Wireless Communications" by Shenjie Huang, Danial Chitnis, Cheng Chen, Harald Haas, Mohammad-Ali Khalighi, Robert K. Henderson, and Majid Safari, delivers a comprehensive overview of single photon counting (SPC)-based OWC. To improve the reliability and achievable data rate of SPC-based OWC systems, a general framework is proposed to incorporate signal pre-processing and post-processing blocks at the transmitter and receiver. The signal processing blocks are designed to effectively mitigate the impact of receiver dead-time and noise signal dependency.

The article "High-Performance OCC with Edge Processing on SPAD and Event-Based Cameras" by Lih Wei Chia and Mehul Motani, presents a camera-based receiver design that utilizes widely available Single-Photon Avalanche Diode (SPAD) arrays along a frontend lens system that enable separation of transmitters. The approach piggybacks OWC on the existing cameras that are part of our lives. With several megabit-per-second throughput potential, the design has potential for use in mobile applications such as vehicle-to-everything communications.

We would like to express our gratitude to all authors for submitting their work to the feature topic and anonymous reviewers for their insightful reviews and suggestions that have helped maintain the high quality of this feature topic.

Biographies

Murat Yuksel [SM] (murat.yuksel@ucf.edu) is a Professor at the ECE Department of the University of Central Florida (UCF), Orlando, FL and a Visiting Scientist at MIT Lincoln Labs. He served as the Interim Chair of ECE at UCF from 2021 to 2022. Prior to UCF, he was a faculty member at the CSE Department of the University of Nevada, Reno, NV. He received his Ph.D. degree in computer science from Rensselaer Polytechnic Institute, Troy, NY in 2002. He worked as a software engineer and held visiting positions at AT&T Labs and Los Alamos National Lab. His research interests are in the areas of networked, wireless, and computer systems with a recent focus on wireless systems, optical wireless, spectrum sharing, network economics, network architectures, and network management. He has been the principal investigator for several projects, funded by the U.S. National Science Foundation, on mobile OWC and multi-element visible light communications. He has been on the editorial boards of *Computer Networks*, *IEEE Transactions on Communications*, *IEEE Transactions on Machine Learning in Communications and Networking*, and *IEEE Networking Letters*. He is a senior member ACM.

Morio Toyoshima [SM] received a Ph.D. in electronic engineering from the University of Tokyo, Japan in 2003. He joined the Communications Research Laboratory (CRL, Ministry of Posts and Telecommunications) in 1994 and shortly after was engaged in research for the Engineering Test Satellite VI (ETS-VI) optical communication experiment. He joined the Japan Aerospace Exploration Agency (JAXA; formerly, NASDA) to develop the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) from 1999 to 2003. He spent one year as a guest scientist at Vienna University of Technology, Austria in 2004. In April 2006, he returned to National Institute of Information and Communications Technology (NICT; formerly CRL), where he performed ground-to-OICETS laser communication experiments in 2006. He was involved in the development of the Small Optical TrAnsponder (SOTA) for 50-kg-class satellites and conducted the first satellite-to-ground quantum communication experiments. He was also involved in the development of the Engineering Test Satellite 9 (ETS-9). He is now the Director General of the Wireless Networks Research Center in NICT since April 2021. He is on the editorial board of *IEEE Transactions on Communications*, and organizes the IEEE ICSOS (International Conference on Space Optics System and Application). He is a fellow member of IEICE, Japan.

Baris I. Erkmen has been active in the development of advanced optical communication and sensing systems for two decades. He is presently CTO at Aalyria Technologies, driving the development of lasercom technology to connect space and ground communication networks. Before joining Aalyria, he was the CEO of Hedron Space (2022–2023), developing an optical data-relay network for Earth-observation satellites. His past responsibilities include Engineering Director of Project Taara at X (2017–2022) where he developed a high-performance, cost effective, and manufacturable wireless optical communication product to expand terrestrial broadband networks that has been deployed to date in hundreds of locations across the world. Prior to that he was the Engineering Lead for Project Loon's Free-Space Optical Communications team (2013–2016), where he and his team developed optical communications technology for a stratospheric platform and demonstrated it over thousands of kms of flights. He has also been the Principal Investigator for NASA's OPALS laser communication demonstration (2009–2013), which successfully demonstrated an optical downlink from the International Space Station to Earth. In 2022, he was elected Fellow of Optica for contributions to the advancement of wireless optical communication systems. His interests encompass the application of both classical and quantum properties of light to enhance communication and sensing capabilities for terrestrial, airborne, and spaceborne systems.