Digital Object Identifier 10.1109/OJCOMS.2020.3045818

Special Issue on: Optical Wireless Communications for Emerging Connectivity Requirements

I. INTRODUCTION

THE INCREASING number of smart devices in different forms and capabilities combined with the worldwide adoption of advanced multimedia applications are contributing to the significant growth of the mobile data traffic. The fifth generation (5G) and beyond-5G wireless networks aim at providing wireless connectivity with very high data rates, low latency, high reliability, and scalability, and will support the emerging Internet-of-Things (IoT) applications and services with massively interconnected devices [items 1), 2) in the Appendix].

Considering the on-going demand for the use of radio frequency (RF) technologies with a limited spectrum in IoT-based applications, optical wireless communication (OWC) systems are seen as a serious complementary or alternative solution to the RF technologies in certain application areas, thus allowing the use of RF in applications with high-degree of mobility. By offering significant technical and operational advantages, OWC has received increasing attention within the research community. It is believed that, OWC, and in particular visible light communications (VLC), will revolutionize the telecommunications marketplace currently dominated by the RF technology [items 3), 4) in the Appendix].

II. PROMISES AND CHALLENGES OF OWC FOR EMERGING APPLICATIONS

In outdoor applications, free-space optical (FSO) communications is well known as a promising wireless access technology offering numerous advantages, including the availability of huge license-free spectrum, low implementation cost, and robustness to RF electromagnetic interference [items 5), 6) in the Appendix]. Current FSO technology promises fiber-like data rates with far lower deployment cost and complexity than fiber alternatives. However, the practical deployment of FSO links and their integration in future wireless networks comes with a number of challenges. In particular, (i) the performance degradation under relatively strong atmospheric conditions; (ii) the requirement to precise beam alignment; and (iii) the vulnerability to adverse weather conditions such as thick fog, low clouds, snow, etc., impose careful link budget estimation and the use of efficient techniques for mitigating turbulence, pointing errors and severe channel loss, in particular in long-haul links [items 5), 7), 8) in the Appendix]. In particular, FSO links on high mobility platforms, require precise and reactive channel estimation and time synchronization in addition to accurate and agile beam tracking to ensure high link reliability. This is also the case for aerial or aerospace FSO links, including inter-satellite and satellite-to-ground links, and unmanned aerial vehicle (UAV) or high-altitude platform (HAP)-based networks.

In indoor applications, VLC has received increasing attention for more than two decades, in particular, for providing high-speed wireless connectivity, which is also usually referred to as Li-Fi. This has been driven by some specific features of the VLC technology (with respect to the general OWC), including the use of light-emitting-diode (LED)-based luminaires for data transmission, and inherent security due to light confinement in most indoor scenarios. Among current research topics on VLC networks, we can mention addressing multiple-access requirements and user mobility [items 9), 10) in the Appendix]. In particular, special attention has been devoted to the design of efficient multi-cell architectures in order to ensure network coverage and user mobility in relatively large indoor spaces. A special case of VLC is when the camera of a smart device is used as the detector, commonly known as optical camera communications (OCC), where data transmission is based on spatial and temporal variations of light intensity. OCC can be regarded as one of enabling technologies for IoT connectivity in future smart environments [item 11) in the Appendix]. The main challenges here include increasing the data rate, which is mainly limited by the camera exposure time and the frame rate.

Another relevant use of OWC is in RF-restricted applications, such as in airplanes and hospitals, where the considerations of electromagnetic interference, data security, and the possible impact of RF waves on the tissues make OWC an interesting alternative technology to RF. Due to practical reasons, the use of infrared communications is the best approach in most use cases. Here, an important step is accurate channel modelling prior to the design of efficient and high-reliability signaling techniques. As for medical applications, we are witnessing nowadays an increasing attention in e-Health solutions in a number of application scenarios with the aim of improving patients' quality of life and reducing health-care expenditures. Therein, medical wireless body-area networks can be used as the main building block, enabling acquisition and transmission of timely data from different medical sensors. The main challenge in such networks include ensuring high reliability, low implementation complexity and energy consumption, high data security, and conformity to eye-safety restrictions [item 12) in the Appendix].

Lastly, the use of OWC in underwater applications has been the subject of extensive research during the past two decades or so. Underwater OWC is in fact a promising technology, allowing for high rates and low latency data transmission over short to moderate transmission ranges, by taking advantage of the directivity of optical beams and the high propagation speed of optical waves in water (compared with acoustic waves), as well as moderate propagation loss (compared with RF). This technology also allows for low energy consumption and relatively small size transceivers, which are essential for the development of high-performance underwater equipment with data transmission capability [items 13), 14) in the Appendix]. However, there still exist many challenges for the widespread deployment of this technology in underwater applications, including dealing with pointing errors and limited localization accuracy, extending the link span, and enhancing the data rate [items 13), 15) in the Appendix].

III. SPECIAL ISSUE AIM AND ACCEPTED PAPERS

The interests and research activities in OWC covering the main three bands of ultraviolet, visible and infrared are continuing to grow, and therefore opening up research and development opportunities, challenges that need addressing by the scientific community at large.

The aim of this Special Issue has been to bring together original research works from both academia and industry to present their views and the latest research and development findings on different aspects of OWC systems, from fundamental to applied. Through a rigorous review process, nine papers, including one invited paper, were accepted for publication. The majority of the papers are related to VLC, which is a very hot topic in the next generation wireless access networks.

The first article (an invited paper), titled "Hybrid SPAD/PD Receiver for Reliable Free-Space Optical Communication," by Huang and Safari, proposes a novel dual-mode receiver for free-space optical (FSO) communications system comprising of an array of single-photon counting avalanche diode and a typical linear photodiode to enhance the link availability under adverse channel conditions. The switching between the two photo-detection modes is enabled by a controller, which adaptively monitors the channel conditions. The resulting enhanced achievable data rates under various weather conditions are demonstrated through extensive performance analyses.

The second article, titled "Performance Trade-Offs of an Optical Wireless Communications Network Deployed in an Aircraft Cockpit," by Joumessi-Demeffo *et al.*, considers the OWC technology for audio communications inside an aircraft cockpit. To study the link performance, channel models for both up- and down-link between the headsets of the four pilots and an access point placed in the ceiling of Airbus A350 cockpit are provided. In addition, based on the IEEE 802.11 medium access control protocol, the effects of the transmit power and the delay are investigated for successful communications, where the trade-off between the two parameters to achieve a given data rate and performance are highlighted.

The third article, titled "LED Half-Power Angle Optimization for Ultra-Dense Indoor Visible Light Communication Network Deployment," by Xu *et al.*, focuses on the unit-area transmission rate of an indoor downlink VLC network with a dense attocell configuration, with binomial-distributed users. The paper considers optimizing the light emitting diode (LED) half-power angle with the aim of maximizing the mean achievable transmission rate per unit area. In addition, the corresponding data rates of the cell-center and cell-edge users are investigated under the user fairness criterion.

The fourth article, titled "Full Field Radiant Flux Distribution of Multiple Tilted Flat Lambertian Light Sources," by Valencia-Estrada *et al.*, studies light source modeling in VLC networks and investigates a more accurate radiant flux distribution, e.g., in the cases of relatively large-dimension emitters such as LED panels or large-area organic LEDs. Flat Lambertian rectangular or circular source models are proposed and validated through actual measurements. The proposed models allow a more accurate estimation of the required link budget, as compared with the classical point-source Lambertian radiation model.

The fifth article, titled "Optimization and Comparison of M-PAM and Optical OFDM Modulation for Optical Wireless Communication," by Mardanikorani *et al.*, considers the suitability of using the optical-orthogonal frequency division multiplexing (OFDM) scheme to address the limited modulation bandwidth of LEDs in VLC networks, and outlines its limitation in terms of peak-to-average power ratio (PAPR) and the need for a high DC-bias level. The performance of DC-biased optical (DCO)-OFDM and classical pulse-amplitude modulation (PAM) signaling are hence contrasted for different signal-to-noise ratio (or the so-called "normalized power budget") levels, by evaluating the required modulation bandwidth and DC-bias, as well as the requirement for bit or power loading in DCO-OFDM.

The sixth article, titled "A High-Precision Positioning Scheme Under Non-Point Visible Transmitters," by Zhao *et al.*, considers indoor visible light positioning and tracking using interacting multiple-model based on the unscented Kalman filter, while taking into account the geometry of the light sources (rather than considering them as point sources). The advantage of the proposed tracking algorithm is demonstrated through numerical simulations for typical application scenarios.

The seventh article, titled "TDMA Scheduling in Spatially Extended LiFi Networks," by Beysens *et al.,* addresses blocking in VLC networks by proposing a computationally efficient scheduling protocol, which is in particular promising for very dense networks, thus allowing improved robustness and a soft handover feature. The proposed scheduling algorithm is based on a time-division contention-free access scheme, which can be regarded as a semi-distributed spatial extension of the time-division multiple-access technique.

The eighth article, titled "Exploiting Blockage In VLC Networks Through User Rotations," by Beysens *et al.*, considers the effect of blocking on the performance of VLC networks and proposes a user-in-the-loop mechanism, where users receive instructions to rotate themselves to minimize beam blocking probability, while trying to block the interfering signals. Based on the proposed system architecture and the user's orientation optimization approach, the presented numerical and experimental results show a significant improvement of the system performance and the individual user experience.

The ninth article, titled "Cooperative Passive Pedestrian Detection and Localization Using a Visible Light Communication Access Network," by Hosseinianfar and Brandt-Pearce, considers the beam blocking in VLC networks (in particular due to pedestrians) from a different angle and proposes a probabilistic method for passive pedestrian detection and localization. The VLC network is then proposed to collect the blocking status and to compute the geometry of the LOS link graph using a cooperative scheme between the users within a room.

The Guest Editorial team sincerely thanks all authors for their contributions to this Special Issue and the reviewers for their precious help and careful consideration of the submissions. We are also grateful to Prof. Octavia A. Dobre, Editor-in-Chief, and Prof. George Karagiannidis and Prof. Jianwei Huang, Associate Editors-in-Chief of the IEEE OJ-COMS, as well as Ms. Rolande N. Kouatang, Editorial Assistant, for their great guidance and assistance.

MOHAMMAD ALI KHALIGHI
Aix-Marseille University,
CNRS, Centrale Marseille,
Institut Fresnel,
Marseille, France.

ZABIH GHASSEMLOOY
Faculty of Engineering and Environment,
Optical Communications Research Group,
Northumbria University,
Newcastle upon Tyne, U.K..

MOHAMED-SLIM ALOUINI
Computer Electrical and Mathematical Science and Engineering Division,
King Abdulah University of Science and Technology (KAUST),
Thuwal, Saudi Arabia.

STEVE HRANILOVIC
Department of Electrical and Computer Engineering,
McMaster University,
Hamilton, ON, Canada.

STANISLAV ZVANOVEC
Department of Electromagnetic Field,
Faculty of Electrical Engineering,
Czech Technical University in Prague,
Prague, Czech Republic.

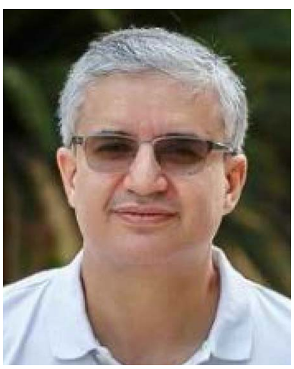
APPENDIX
RELATED WORK

1) Z. Zhang *et al.*, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.
2) E. Yaacoub and M.-S. Alouini, "A key 6G challenge and opportunity—Connecting the base of the pyramid: A survey on rural connectivity," *Proc. IEEE*, vol. 108, no. 4, pp. 533–582, Apr. 2020
3) Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2019.
4) Z. Ghassemlooy, L. N. Alves, S. Zvànovec, and M. A. Khalighi, *Visible Light Communications: Theory and Applications*. Boca Raton, FL, USA: CRC Press, 2017.
5) M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 4th Quart., 2014.
6) A. Trichili, M. A. Cox, B. S. Ooi, and M.-S. Alouini, "Roadmap to free space optics," *J. Opt. Soc. America B*, vol. 37, no. 11, pp. A184–A201, Aug. 2020.
7) A. A. Farid and S. Hranilovic, "Outage capacity optimization for free-space optical links with pointing errors," *J. Lightw. Technol.*, vol. 25, no. 7, pp. 1702–1710, Jul. 2007.
8) M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, and E. Bentley, "Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions," *J. Lightw. Technol.*, vol. 31, no. 11, pp. 1720–1726, Jun. 1, 2013.
9) M. W. Eltokhey, M. A. Khalighi, A. S. Ghazy, and S. Hranilovic, "Hybrid NOMA and ZF pre-coding transmission for multi-cell VLC networks," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 513–526, Apr. 2020.
10) P. A. Haigh, Z. Ghassemlooy, S. Rajbhandari, and I. Papakonstantinou, "Visible light communications using organic light emitting diodes," *IEEE Commun. Mag.*, vol. 51, no. 8, pp. 148–154, Aug. 2013.
11) O. I. Younus *et al.*, "Data rate enhancement in optical camera communications using an artificial neural network equaliser," *IEEE Access*, vol. 8, pp. 42656–42665, 2020.
12) O. Haddad, M.-A. Khalighi, S. Zvanovec, and M. Adel, "Channel characterization and modeling for optical wireless body-area networks," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 760–776, Jun. 2020.
13) M. A. Khalighi, H. Akhouayri, and S. Hranilovic, "Silicon-photomultiplier-based underwater wireless optical communication using pulse-amplitude modulation," *IEEE J. Ocean. Eng.*, vol. 45, no. 4, pp. 1611–1621, Oct. 2020.
14) D. Zhang, I. N'Doye, T. Ballal, T. Y. Al-Naffouri, M.-S. Alouini, and T.-M. Laleg-Kirati, "Localization and tracking control using hybrid acoustic–optical communication for autonomous underwater vehicles," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10048–10060, Oct. 2020.
15) A. Celik, N. Saeed, B. Shihada, T. Y. Al-Naffouri, and M.-S. Alouini, "A software-defined opto-acoustic network architecture for Internet of underwater things," *IEEE Commun. Mag.*, vol. 58, no. 4, pp. 88–94, Apr. 2020.

MOHAMMAD ALI KHALIGHI (Senior Member, IEEE) received the Ph.D. degree in telecommunications from the Institut National Polytechnique de Grenoble, Grenoble, France, in 2002.

He is currently an Associate Professor with École Centrale Marseille, Marseille, France, and the Head of the Optical Communications for IoT Group, Fresnel Institute Research Laboratory. He is serving as the Project Coordinator for the H2020 ITN MSCA VisIoN Project (Visible-Light-Based Interoperability and Networking) and the Action Chair for the COST Action CA19111 NEWFOCUS (European Network on Future Generation Optical Wireless Communication Technologies). He has coedited the book *Visible Light Communications: Theory and Applications* (CRC Press, 2017). His main research interests include signal processing for wireless communication systems with an emphasis on the physical layer aspects of free-space, underwater, and indoor visible-light optical communications. He was the co-recipient of the 2019 Best Survey Paper Award of the IEEE Communications Society. He is currently serving as the Editor-at-Large for the IEEE TRANSACTIONS ON COMMUNICATIONS. He has also served as an Associate Editor for the *IET Electronics Letters* as well as a Guest Co-Editor for the *Optik* (Elsevier).

ZABIH GHASSEMLOOY (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electrical and electronics engineering from Manchester Metropolitan University in 1981, and the M.Sc. and Ph.D. degrees from the University of Manchester, U.K., in 1984 and 1987, respectively. From 1987 to 1988, he was a Postdoctoral Research Fellow with City University, U.K. From 1988 to 2004, he was with Sheffield Hallam University, U.K., and from 2004 to 2014, he was with the Faculty of Engineering and Environment, Northumbria University, U.K., as an Associate Dean Research, and is currently the Head of the Optical Communications Research Group. He has been a Research Fellow since 2016 and a Distinguished Professor since 2015 with the Chinese Academy of Science. He was the Vice-Chair of EU Cost Action IC1101 from 2011 to 2016 and is the Vice-Chair of the EU COST Action CA19111 NEWFOCUS (European Network on Future Generation Optical Wireless Communication Technologies) from 2020 to 2024. He has published over 900 papers (more than 355 journals and eight books), 100 keynote/invited talks, and supervised ten Research Fellows and 65 Ph.D. students. His research interests are in the areas of optical wireless communications, free space optics, visible light communications, hybrid RF, and optical wireless communications. He is the Chief Editor of the *British Journal of Applied Science and Technology* and the *International Journal of Optics and Applications*, an associate editor of a number of international journals, and a co-guest editor of a number of special issues OWC. He has been the Vice-Chair of the OSA Technical Group of Optics in Digital Systems since 2018 and the Chair of the IEEE Student Branch at Northumbria University, Newcastle upon Tyne, since 2019. From 2004 to 2006, he was the IEEE UK/IR Communications Chapter Secretary, the Vice-Chairman from 2006 to 2008, the Chairman from 2008 to 2011, and the Chairman of the IET Northumbria Network from October 2011 to 2015. He is a CEng and a Fellow of SOA and IET.



MOHAMED-SLIM ALOUINI (Fellow, IEEE) was born in Tunis, Tunisia. He received the Ph.D. degree in electrical engineering from the California Institute of Technology, Pasadena, CA, USA, in 1998. He served as a Faculty Member with the University of Minnesota, Minneapolis, MN, USA, then with Texas A&M University at Qatar, Education City, Doha, Qatar before joining the King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia, as a Professor of Electrical Engineering in 2009. His current research interests include modeling, design, and performance analysis of wireless communication systems.

STEVE HRANILOVIC (Senior Member, IEEE) received the B.A.Sc. degree (with Hons.) in electrical engineering from the University of Waterloo, Canada, in 1997, and the M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Toronto, Canada, in 1999 and 2003, respectively.

He is a Professor with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON, Canada. From 2010 to 2011, he spent his research leave as a Senior Member and a Technical Staff with the Advanced Technology for Research in Motion, Waterloo, Canada. His research interests are in the areas of free-space and optical wireless communications, digital communication algorithms, and electronic and photonic implementation of coding and communication algorithms. He is the author of the book *Wireless Optical Communication Systems* (New York: Springer, 2004). He is a licensed Professional Engineer in the Province of Ontario. In 2016, the title of University Scholar was conferred upon him by McMaster University. He currently serves as an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS in the area of optical wireless communications.

STANISLAV ZVANOVEC (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees from the Faculty of Electrical Engineering, Czech Technical University (CTU), Prague, in 2002 and 2006, respectively. To date, he works as a Full Professor and the Deputy Head of the Department of Electromagnetic Field and the Chairperson of Ph.D. Branch at CTU. His current research interests include free space optical and fiber optical systems, visible light communications, OLED, and RF over optics and electromagnetic wave propagation issues for millimeter-wave band. He is the author of two books (and coauthor of the recent book *Visible Light Communications: Theory and Applications*), several book chapters and more than 300 journal and conference papers.