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Guest Editorial
Optical Wireless Communication Systems

Zabih Ghassemlooy, Stanislav Zvanovec, Mohammad-Ali Khalighi, Wasiu O. Popoola and Joaquin Perez

***Abstract*— The emerging field of optical wireless communication (OWC) systems is seen as potential complementary technology to the radio frequency wireless communications in certain applications. It is deemed as a possible technology in the future 5th Generation communication networks to address the spectrum congestion and improve the system's capacity. More research and developments in OWC is still needed in order for it to be adopted in current and future communication systems. This special issue brings together research papers on OWC covering free space optic, visible communications and ultraviolet communications.**

***Index Terms*—optical wireless communication, free space optics, OWC, FSO, visible light communication, ultraviolet, VLC**

I. Introduction

The world of wireless communications has gone through tremendous changes in the last three decades. In the last few years, we have seen a surge in the number of mobile subscribers requiring access to high-speed wireless services at any time and any place. Currently, there are over 7.2 billion gadgets, and the annual mobile traffic is expected to reach 3 Zetabyte by 2019 [1]. This growth (in speed and applications) has motivated both mobile operators, researchers and the standardization bodies to continuously develop new transmission technologies, protocols, network infrastructure solutions and standards to enhance the minimum technical system performance requirements outlined in Table 1 [2]. Future technologies that will require reliable high-speed wireless connections include sensor networks, delay tolerant networks, vehicular communications networks, cognitive networks, manufacturing, medicine, mega data centers etc. [3–7]. The wireless technologies will also benefit from a number of techniques including advanced signal processing algorithms at the physical layer, novel environment-aware applications, wireless network coding, physical-layer security and interference alignment among others.

In wireless communications network throughput (bit/s in an area) is a function of three main parameters of the cell density (cells/area), the available frequency spectrum (Hz), and the spectrum efficiency (bits/Hz/cell). Current 4th generation (4G) communication networks are mainly optimized for a peak data rate of a few 100 Mbps. This is expected to increase to 1 Gbps or beyond in the future 5th generation (5G) networks, which should be able to cater for the Internet of things (IoT) [8]. The deployment of IoT is a major challenge for future communications networks, which will be extensively deployed in smart environments, smart building buildings, security and safety, agriculture, manufacturing, device-to-device communications, etc. [9].

The frequency spectrum is a precious and costly resource, and its scarcity is the main challenge as the number of users is continuously growing at an exponential rate. Addressing this challenge requires innovation in many areas including novel ways for spectrum sensing, sharing, borrowing and reuse, reduced the cell size and increase cell density (i.e., more complexity), improving the frequency reuse strategy, reducing the interference (i.e., lower transmit power levels), advanced modulation and coding schemes, parallel transmission (e.g., massive multiple input multiple output (MIMO), and more efficient protocols. In addition, to reduce the pressure on wireless networks using the licensed spectrum and improve the network capacity, the emphasis is to use wireless technologies (typically low power and shorter range), which operates in the unlicensed spectrum i.e., ultra-wideband, 60-GHz, near-field communications, TV white space, WiFi, Bluetooth, etc.

Table 1. Technical system performance requirements

Parameter	Value
Peak data rate	20 for Downlink – based on 5G IMT
Average spectral efficiency	9 bps/Hz - Downlink indoor ~8 bps/Hz – Downlink urban ~3 bps/Hz – Downlink rural
Traffic capacity	10 Mbps/m^2 - Downlink
Latency (user)	Low - 4 ms for enhanced mobile broadband
Energy efficiency	High – Lowe average power with long sleep period
Bandwidth	Minimum of 100 MHz, increasing up to 1 GHz @ frequencies > 6 GHz
Mobility	High – Up to 500 km/s

Z. Ghassemlooy is with the Optical Communications Research Group, NCRLab, Faculty of Engineering and Environment, Northumbria University, Newcastle, UK; Email: z.ghassemlooy@northumbria.ac.uk,
S. Zvanovec is with 1Department of Electromagnetic Field, Czech Technical University in Prague, Prague, Czech Republic; Email: xzvanove@fel.cvut.cz,
A. Khalighi is with Institut Fresnel, École Centrale Marseille, Marseille, France ; Email : Ali.Khalighi@fresnel.fr
W. O. Popoola is with Institute for Digital Communications, School of Engineering, The University of Edinburgh, UK; Email: wpopoola@staffmail.ed.ac.uk
J. Perez is with Photonics Research Labs, ITEAM research institute, Universitat Politècnica de València, Valencia, Spain; Email: joapeso@upv.es

II. Optical wireless communications

An alternative and a complementary option would be to adopt the optical wireless communications (OWC) technology, which covers the ultraviolet, infrared and visible bands (from 350 to 1550 nm). OWC offers a huge unregulated bandwidth (orders of magnitude higher than RF) and can deliver data rates compatible with the optical fiber communications in the infrared band [10–13]. OWC offer a number of advantages including (i) fast deployment in difficult terrain, and situations; (ii) relatively low cost compared to RF; (iii) free from RF interference; (iv) inherent security (light can be confined within opaque walls); and (v) high energy efficiency.

In future wireless communication networks, co-existence and co-use of OWC, cellular and WiFi (with over 500 MHz of available bandwidth in the unlicensed bands of 2.4 GHz and 5 GHz) systems could be considered as one possible option to the spectrum management and easing of the spectrum congestion [14]. In 5G, a combination across all frequency bands could be important, which could be achieved by allocating lower frequencies for wide area coverage, higher frequency bands (i.e., millimetre (20–100 GHz) and OWC for access networks and personal area communications as well as short range indoor links. The latter is best suited for the visible band (390–700 nm), which is commonly referred to as visible light communications (VLC). VLC has seen a growing research activities in recent years. VLC takes a full advantage of visible light emitting diodes (LEDs) for the dual purpose of illumination and wireless data communications at very high speeds.

Many of the current wireless communication technologies share key technological similarities, and this is also likely to be in future wireless systems. The key technology requirements outlined in Table 1, which are mostly intended for the RF technologies, are very challenging. The peak rate, which is for the ideal conditions, determine the maximum offered bandwidth, coding and modulation schemes that could be supported by the access technology, whereas low latency requirement points to the use of small cells (nan—and femto-cells) in both indoor and outdoor environments with low transmit time interval. The high-energy efficiency requirement sets the tone for low power consumption and highly intelligent power management system. The OWC system, seen as a complementary technology to the RF, can address these requirements, and therefore could be adopted in multitude of applications including [11,12]:

- Broadband internet in rural areas [15] – Mostly FSO and ultraviolet systems that can replace optical fiber access technologies such as fiber to the home (FTTH) in order to provide connectivity between in-building networks and to broadband and backbone data networks.
- Inter-building connectivity and electronic commerce [16] – FSO and visible light communications (VLC), which provide speed, flexibility and high security.
- Audio and video streaming [13] – For live broadcasting of sporting events, in emergency situation, indoor entertainment etc.
- Unmanned aerial vehicle and underwater vehicles [16,17] – FSO, and VLC systems can be used in military surveillance, monitoring traffic and disaster areas, or broadcasting vital data.
- Space to ground and inter-satellite links to transfer extremely higher amount of data by FSO technology then in RF domain [18].
- High-secure quantum key distribution based OWC for long haul systems – satellite to ground [19].
- OWC based secure codifying techniques – Optical orbital angular momentum – for mobile and IoT scenarios [20].
- Intelligent transportation system [11] – Mostly VLC in vehicle-to-vehicle and vehicle-to-infrastructure safety communications, and entertainment within vehicles.
- Interand intra-chip communications [21].
- Medical and manufacturing [22] – Wearable medical devices with wireless transmission capabilities are a key technology for monitor health and wellbeing of people. OWC is seen as a potential candidate for medical wireless body area networks with high data rates capabilities.
- Wireless sensor network [23] – Sensor data is extremely important to in underwater, manufacturing etc. for condition-based monitoring, machine diagnosis and process adaptation to new requirements etc.

i) OWC Challenges

However, in OWCs a number of challenges needs addressing prior to its widespread deployment. This special issue on OWC highlights the recent research and development in this emerging field. The special issue is based on the extended version of the selected best papers presented at the 5th Colloquium on Optical Wireless Communications as part of the 10th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), which was held in Prague, Czech Republic in July 2016 as well as selected papers from open call.

This special issue includes a collection of 15 papers, which will undoubtedly contribute to addressing some of the issues that hamper the widespread deployment of OWC systems. Papers are grouped into three areas of: a) FSO, b) VLC and c) UV communications.

ii) Free space optics

The first three papers deal with different aspects of FSO.

Replacing existing optical fibers currently being deployed in the communication networks and replacing or installing new ones is highly time-consuming and costly especially in dense urban areas. Alternatively, the FSO technology, which offers higher data rates and longer transmission span, could be deployed rapidly over a transmission spans of up to a fewkilometers. Jan Bohata et al in "*Adaptation of Transmitting Signals over Joint Aged Optical Fiber and Free Space Optical Network Under Harsh Environments*", propose the use of existing ageing optical fiber infrastructure together with free space optics links as a part of modern optical communication networks. They demonstrate adaptation of polarization multiplexed radio over fiber and radio over FSO systems as well as 10 Gbps non-return-to-zero on-off-keying based intensity modulation with the direct detection system, which is a cost-effective transmission system used in passive optical networks. Also investigated is the effect of atmospheric turbulence on the performance of 100 and 200 Gbps return-to-zero differential quadrature phase shift keying with direct detection hybrid aged optical fiber and FSO network.

A paper by Chadi Abou-Rjeily on "*Two-by-Two User Grouping for Enhanced Multipoint-to-Multipoint Free Space Optical Communications with Pulse Position Modulation*," considers the problem of multipoint-to-multipoint FSO communications with any number of users. A novel cooperation scheme where the users are grouped together in groups of two for the sake of achieving enhanced diversity orders in a simple manner is proposed. Instead of transmitting independent binary pulse position modulation symbols over each *N* available links in a non-cooperative manner, the information from the different users is combined and encoded in a joint manner. A method for performing the joint encoding is presented. Also proposed is the structure of the 4-ary augmented constellation to be associated with the proposed cooperation scheme. An asymptotic analysis of the average bit error rate over gamma–gamma fading channels as well as the achievable diversity orders under background noise are provided.

In FSO systems, to enhance the spectral efficiency, adaptive modulation is considered, where modulation orders is changed based on the channel conditions in turbulent fading channels. A paper by Wael G. Alheadary et al on "*Performance Analysis of Multihop Heterodyne Free-Space Optical Communication Over General Malaga Turbulence Channels with Pointing Error*," investigates the end-to-end performance of a FSO with amplify-and-forward channel-state-information-assisted relaying system using heterodyne detection over Malaga turbulence channels together with the pointing error employing rectangular quadrature amplitude modulation. Exact closed-form expressions for the average bit-error rate for adaptive/non-adaptive modulation, achievable spectral efficiency, and ergodic capacity by utilizing generalized power series of Meijer's G-function are given. To validate the proposed work at higher power regime, asymptotic closed form expressions are also provided.

iii) Visible light communications

The next seven papers are related to VLC.,

The dynamic range of LEDs is limited therefore making it challenging to fully accommodate the swings of signal with high peaks on LED intensity without causing clipping. When happens, it results in signal distortion and degradation of the system performance. The paper by Funmilayo B. Offiong et al on "*Analysis of PAPR in Optical OFDM Systems with Grouped LEDs*" extends the study of the pilot assisted technique in the spatial domain optical OFDM by using grouped LEDs to theoretically characterise the peak-to-average-power ratio (PAPR) distribution. The order statistics is applied to quantify the PAPR reduction gain. Closed-form result of the PAPR distribution of the technique is presented using the complementary cumulative distribution function, which gives the probability of a PAPR value exceeding a certain threshold level. The theoretical study provides a fast and efficient means of determining the trade-off between the PAPR reduction gain required and computational and hardware complexities of the system.

Support vector machine (SVM), a widely used machine learning algorithms, has been used to address a range of engineering problems, notably in statistical signal processing, pattern recognition, image analysis, digital communications, and in VLC for equalizations and for combating the multipath induced intersymbol interference and the co-channel interference. A paper by Youli Yuan et al on "*SVM-based Detection in Visible Light Communications*," introduces an SVM algorithm for 8-Superposed pulse amplitude modulation and direct-current-biased OFDM VLC system in order to improve the system performance. Without any prior knowledge or heuristic assumptions, SVM is used to construct a classify model from only a few training data set. The experiment results presented show that the SVM detection offers improved bit error rate performance compared with the traditional direct decision method.

In VLC systems the threat of eavesdropping by malicious user is, nevertheless, still possible within the illuminated area, especially in the presence of multiple users. In addition to the traditional encryption techniques at the network layer, the physical layer security (PLS) is been seen as a promising approach to further increase the security level. There are only a few studies on PLS in VLC systems as compared to the RF based wireless communications. A paper by Thanh V. Pham et al on "*Secrecy Sum-Rate of Multi-User MISO Visible Light Communication Systems with Confidential Messages*," studies the information theoretic secrecy sum-rate for multi-user multiple-input single-output VLC systems with confidential messages. The well-known zero-forcing precoding technique is used to ensure confidentiality between the legitimate users and, at the same time, to prevent eavesdropper(s) from obtaining any information. Analytical investigation of a novel bound on the secrecy sum-rate of all legitimate users in the proposed systems is carried out, which is valid under a high signal-to-noise ratio regime. The secrecy sum-rate performance is derived for two scenarios: known and unknown eavesdropper's channel state information at the transmitter.

Omer Narmanlioglu et al in "*Performance Analysis and Optimization of Unipolar OFDM Based Relay-Assisted Visible Light Communications*," consider a relay-assisted VLC system by using an intermediate light source to extend the transmission range. Based on the IEEE 802.15.7r1 VLC reference channel model, two different light sources (i.e., a ceiling light and a desk lamp serving as the source and relay terminals, respectively) in a typical office environment is adopted. The unipolar optical

OFDM scheme is adopted, where the desk light performs amplify-and-forward relaying to assist the ceiling light and operates in a half-duplex mode. In addition, the enhanced unipolar OFDM, which doubles the spectral efficiency at the cost of additional computational complexity is considered. The analyses for the bit error rate performance of the proposed system for the two OFDM types and quantify performance improvements over point-to-point (i.e., no relaying) VLC systems are provided. Furthermore, to improve system performance, optimal power allocation between source and relay terminals is also investigated.

In VLC spatial reuse enables a highly directional communications, thus making it possible for the coexistence of a number of non-interfering links in close proximity. Spatial reuse strongly depends on the receiver's field of view and LED's light coverage. A paper by F. Seguel et al on "*A Novel Strategy for LED Re-utilization for Visible Light Communications*," presents a resource allocation optimization model for a downlink indoor VLC system. The optimization problem is formulated as a mixed integer binary problem, where a centralized smart coordinator solves the problem in order to assign efficiently channels to the users. The optimization problem is solved with two different Cuckoo Search algorithm based approaches. These were tested for receivers with different field of view that are randomly placed within the coverage area and for different transmitters.

In VLC systems, it is common to assume that both the interference and user signal-to-interference ratio are Gaussian. This Gaussian interference assumption can be partially justified by the central limit theorem. However, in an indoor VLC, the number of transmitter-receiver pairs is typically small due to the limited number of LEDs in a room area, and therefore the central limit theorem may not be applicable after all. A paper by Yi Chen et al on "*BER Analysis and Power Control for Interfering Visible Light Communication Systems*," considers such a case by dispensing with the Gaussian assumption on the interference and analyses the BER performance of on/off keying intensity modulation VLC system. The BER expressions under an exact analysis and using Gaussian model are derived, and are compared with simulation results. It is shown in an example of four LEDs that the Gaussian interference model is generally pessimistic. Therefore, a new approximation on BER, which is numerically shown to be close to the exact BER, is proposed. Based on this, a power control problem is investigated and a successive convex approximation algorithm to find a solution is proposed.

A contribution by Ata Chizari et al on "*Visible Light for Communication, Indoor Positioning, and Dimmable Illumination: A System Design Based On Overlapping Pulse Position Modulation*", outlines the need to design a VLC system with improved spectral efficiency and reduced power requirement. The dimming control is addressed by changing the code weights while keeping the code lengths of overlapping pulse position modulation symbols in an indoor environment. Considering the illumination standards within a typical room, the interval for dimming percentage is first determined followed by calculation of the maximum data rate for inter-symbol interference free transmission for the dispersive channel. Trellis coded modulation is adopted to take advantage of the corresponding coding gain, which results in improved power requirement of OPPM. The one-persistent carrier sense multiple access MAC protocol is proposed in order to enable two dimensional positioning with an optimum channel access for unique code transmission.

iv) Ultra violet communications

The final papers deal with the uultraviolet (UV) non-line-of-sight wireless communication networks, which are being adopted in three-dimensional space such as formation flying and holding, underwater communication networks, and ground-to-air communications. Taifei Zhao et al in "*A Networking Strategy for Three-dimensional Wireless Ultraviolet Communication Network*," propose a networking strategy for three-dimensional wireless UV communication network in order to optimize the coverage, connectivity and the survivability. Based on the different communication parameters of the apex angle, transmit power, data rate, error probability and node density, modulations and the noise model the performance of the proposed is simulated and analysed. Also investigated is the deployment cost of networks with nodes located in different positions and regions of interest with obstacles. An optimum deployment scheme, which considers the coverage ratio, connectivity and deployment cost, is given.

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Professor Zabih (Fary) Ghassemlooy – received the B.Sc. degree (Hons.) in electrical and electronics engineering from Manchester Metropolitan University, Manchester, U.K., in 1981, and the M.Sc. and Ph.D. degrees from the Institute of Science and Technology, Manchester, University of Manchester, U.K., in 1984 and 1987, respectively. From 1987–1988, he was a PostDoctoral Research Fellow with City University, U.K. 1988 he joined Sheffield Hallam University as a Lecturer, becoming a Reader in 1995 and became a Professor in optical communications in 1997. 2004 joined the University of Northumbria (UNN), Newcastle, as an Associate Dean (AD) for research with the School of Computing, Engineering, and Information Sciences, and from 2012 to 2014, he was AD of Research and Innovation, Faculty of Engineering, UNN, UK, where he currently is Head of the Northumbria Communications Research Laboratories. In 2001 he was awarded the Tan Chin Tuan Fellowship in Engineering from the Nanyang Technological University in Singapore. In 2016 he become a Research Fellow at the Chines Academy of Science, and since 2015 has been a Distinguished Professor with the Chinese Academy of Sciences, Quanzhou, China. He is a Visiting Professor at the University Tun Hussein Onn Malaysia, Malaysia (2013–2017), and Huaqiao University, Quanzhou, China (2017–18). He published over 698 papers (262 journals and 6 books), over 88 keynote and invited talks, and supervised 57 Ph.D. students. His research interests include optical wireless communications, free space optics, and visible light communications with funding from UK, EU and industry including the most recent projects (i) EU Horizon 2020 ITN MSCA project on Visible light based Interoperability and Networking (ViSioN) (2017-2-20), and (ii) UK EPSRC MARVEL (EP/P006299/1) 2017–2020 etc. He was the Vice-Chair of EU Cost Action IC1101 (2011-16). He is the Chief Editor of the British Journal of Applied Science and Technology and the International Journal of Optics and Applications. He is the fellow of the IET, a senior member of IEEE, and a member of OSA. He is a co-author of a CRC book on "Optical Wireless Communications – Systems and Channel Modelling with Matlab (2012); and co-editor of four books including the Springer book on "Optical Wireless

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http://soe.northumbria.ac.uk/ocr/people/ghassemlooy/

Prof. Stanislav Zvanovec received his M.Sc. and Ph.D. degrees from the Faculty of Electrical Engineering, Czech Technical University (CTU) in Prague in 2002 and 2006, respectively. To date, he works as a full professor and deputy head of the Department of Electromagnetic Field and chairperson of PhD branch at CTU. His current research interests include Free Space Optical and fiber optical systems, Visible Light Communications, OLED, RF over optics and electromagnetic wave propagation issues for millimetre wave band. He is the head of Free-space and fiber optics group at CTU (optics.elmag.org). Till 2014 he was a chair of the Joint MTT/AP/ED/EMC chapter of the IEEE Czechoslovakia Section and he is head of the Commission F "Wave Propagation and Remote Sensing" of the Czech National URSI Committee. He leads research and participates within in the frame of international projects ESA PECS no. 98069, ESA 4000105298/12/NL/CLP, ACE 2, EU COST projects IC1101 OPTICWISE (Optical Wireless Communications – An Emerging Technology) as vice chair of WG1, IC0802, IC0603, CA16220, Centre for quasi-optical systems and terahertz spectroscopy, holder of projects national TACR and GACR projects, participates in Visible light based Interoperability and Networking (ViSioN) European ITN MSCA project etc. He is author of two books (co-author of recent book Visible Light Communications: Theory and Applications), several book chapters and more than 200 journal and conference papers, and holder of patent for All-optical packet switch. zvanovec.elmag.org

Dr Mohammad-Ali Khalighi is Associate Professor in Ecole Centrale Marseille and head of "Telecommunications and Antenna Processing" in Fresnel Institute research lab. His main research areas of interest 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. So far he has served as the Technical Program Committee member for more than 20 international conferences and workshops in the communications area and is currently serving as Associate Editor for IEEE Transactions on Communications. Also, he was the Vice Chair of WG2 of the FP7 IC1101 COST Action on optical wireless communications and is the project coordinator for the H2020 ITN MSCA "VISION" on visible-light communications. Dr. Khalighi is the recipient of the Scientific Excellence Award from the French Ministry of Research and Higher Education for the period of 2009–2017.
http://www.fresnel.fr/perso/khalighi/index.htm

Dr Wasiu O. Popoola is currently a university lecturer and chancellor's fellow in the Institute for Digital Communications, School of Engineering at the University of Edinburgh, UK. During his PhD, he was awarded the 'Xcel Best Engineering and Technology Student of the year 2009,. He has published over 80 journal articles/conference papers/patent and over seven of those are invited papers. One of his journal articles ranked No. 2 in terms of the number of full text downloads within IEEE Xplore in 2008, from the hundreds of papers published by IET Optoelectronics since 1980. Another paper he co-authored with one of his PhD students won the best poster award at the 2016 IEEE ICSAE Conference. He also co-authored the book 'Optical Wireless Communications: System and Channel Modelling with MATLAB, published by CRC in 2012, and several other book chapters (one with over 10000 downloads as of Sept. 2014 since its publication in 2010). Popoola is a senior member of the IEEE, an associate editor of the IEEE Access journal and Guest Editor for Elsevier Journal of Optik (special issue on optical wireless communications) in 2017 and Technical Program Committee member for several conferences. He was an invited speaker at various events including the 2016 IEEE Photonics Society Summer Topicals. Popoola has primary research interest in optical communications including visible light communications, free-space optical communication and fiber communication. Personal webpage: http://www.optical-communications.eng.ed.ac.uk/

Dr Joaquin Perez is a researcher at Photonics Research Labs, ITEAM research institute, Universitat Politècnica de València, Spain. His research interests include microwave photonics, optical wireless communications, quantum optics, photonics integrated circuits and optical access networks. He has participated in several international research projects, e.g., IST-UROOF, ICT-UCELLS, EU COST actions IC0802, IC1101 and CA16220 "European Network for High Performance Integrated Microwave Photonics". He has served as reviewer and committee member for ECOC, ICC, GLOBECOM, VTC, CSNDSP, OSA, IEEE and others. Dr Perez was awarded the Spanish "Juan de la Cierva" postdoctoral fellowship during the period 2014–2016. He is serving as active IEEE and IET member since 2006. He has published more than 60 works in recognized international journals and conferences. www.joaquinperezsoler.es