



# VISIBLE LIGHT COMMUNICATIONS THEORY AND APPLICATIONS

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Edited by

Zabih Ghassemlooy • Luis Nero Alves  
Stanislav Zvánovec • Mohammad-Ali Khalighi

# **Visible Light Communications**

## **Theory and Applications**

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# **Visible Light Communications**

Theory and Applications

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## Editors

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**Zabih Ghassemlooy** received the BSc (Hons) degree in electrical and electronics engineering from Manchester Metropolitan University, UK, in 1981, and the MSc and PhD degrees from the University of Manchester Institute of Science and Technology, UK, in 1984 and 1987, respectively. During 1987–1988, he was a postdoctoral research fellow at City, University of London, UK. In 1988, he joined Sheffield Hallam University, UK, as a lecturer, becoming a professor in optical communications in 1997. In 2004, he joined the Northumbria University, Newcastle upon Tyne (UNN), UK, as an associate dean for research (ADR) in the School of Computing and Engineering. During 2012–2014, he was an ADR in the faculty of engineering, UNN. Currently, he heads the Northumbria Communications Research Laboratory and Optical Communications Research Group. Dr. Ghassemlooy is a visiting professor at Universiti Tun Hussein Onn Malaysia. His research interests are in optical wireless communications, free-space optics, and visible light communications. He has published over 600 articles in 220 journals and 4 books and supervised 50 PhD students. He was the vice-chair of EU Cost Action IC1101 during 2006–2008. He was the IEEE vice-chairman in 2004–2008, the IEEE chairman in 2008–2011, and the chairman of the IET Northumbria Network from October 2011–2015.



**Luis Nero Alves** graduated in 1996 and received his MSc degree in 2000, both in electronics and telecommunication engineering from the University of Aveiro, Portugal. In 2008, he obtained the PhD degree in electrical engineering from the University of Aveiro. His PhD thesis was on high bandwidth–gain product amplifiers for optical wireless applications. Since 2008, he has been the lead researcher at the Integrated Circuits Group from the Instituto de Telecomunicações, Aveiro. His current research interests are aligned with the IC1101 COST action (OPTICWISE) on optical wireless communications, where he is an active member. Dr. Alves has also worked on several nationally (VIDAS and EECCO, both from FCT) and internationally (LITES–CIP, PADSIC–FP7, and RTMGear–FP7) funded research projects, and industrial contracts.



**Stanislav Zvánovec** received his MSc and PhD degrees from the Czech Technical University in Prague in 2002 and 2006, respectively. To date, he works as a full professor and a vice head of the Department of Electromagnetic Field and a leader of the Free-Space and Fiber Optics Group. His current research interests include free space and fiber optical systems and electromagnetic wave propagation issues for quasioptical and millimeter wave bands. Until 2014, he was a chair of the Joint MTT/AP/ED/EMC chapter of the IEEE Czechoslovakia Section, and is currently the head of the Commission F of the Czech National URSI Committee. Research within the frame of international ESA projects, EU COST projects IC1101 OPTICWISE (vice-chair of WP1), IC0802, IC0603, ACE 2, Centre for Quasioptical Systems and Terahertz Spectroscopy, and others, holder of several national projects.

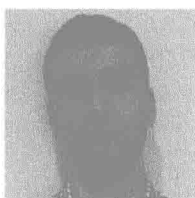


**Mohammad-Ali Khalighi** received his PhD degree in telecommunications from Institut National Polytechnique of Grenoble, France, in 2002. From 2002 to 2005, he was with GIPSA-lab, Télécom Paris-Tech, and IETR-lab as a postdoctoral research fellow. He joined École Centrale Marseille and Institut Fresnel in 2005, where he currently holds an associate professor position. 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, Dr. Khalighi has coauthored more than 80 journal articles and conference papers on these topics. He has served on the Technical Program Committee of more than 18 international conferences and workshops in the communications area, and the TPC co-chair of the International Workshop on Optical Wireless Communications 2015. Also, he was the vice-chair of Working Group 2 of the FP7 IC1101 COST Action on optical wireless communications.

National University, Busan, South Korea. He joined the Mobile Communication Research Laboratory of Plymouth University, UK, as a visiting research fellow in 2004. He was a visiting professor at Pennsylvania State University, University Park, USA, in August 2006 and also at Chiba University, Japan, in September 2015. He served as the executive director of the Office of International Relations, Pukyong National University, from August 2008 to July 2012. He is a member of the Editorial Board for *Wireless Personal Communications*, Springer. He has published over 60 articles in the areas of optical wireless communications and mobile radio communications.



**Petr Chvojka** received his MSc degree in wireless communications from the Czech Technical University in Prague in 2013. He now works toward his PhD in the Department of Electromagnetic Field at the same university where he is a member of the Free-Space and Fiber Optics Team. He was on internships at Ben Gurion University of the Negev, Israel, and Northumbria University, Newcastle upon Tyne, UK, in 2013 and 2014, respectively. He involved in several research projects such as FP7 EU COST IC1101 OPTICWISE (Optical Wireless Communications—An Emerging Technology) and Research of Ambient Influences on Novel Broadband Optical Wireless Systems (LD12058). His current research interests include visible light communications, organic LEDs, and wireless optical communications.



**Tamás Cseh** received the BS and MS degrees in electrical engineering from the Budapest University of Technology and Economics, Hungary. He commenced his PhD studies in 2011, and he is currently a research assistant at the Department of Broadband Infocommunication and Electromagnetic Theory, Budapest University of Technology and Economics. His research interest includes optical communication with multimode fibers, radio over fiber systems, and dispersion compensation methods and modulation formats in subcarrier optical networks. He has authored and coauthored about 17 articles. He is a member of the Scientific Association for Infocommunications, Hungary (HTE).



**José Luis Cura** received his PhD degree in electrical engineering from the University of Aveiro, Portugal, in 1999. He is currently an assistant professor in the Department of Electronics, Telecommunications and Informatics at the same university. Dr. Cura has been a member of the Institute of Telecommunications since its foundation, where he has been involved in various projects in the CMOS analog circuit design area.

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## Contributors

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**Tunçer Baykaş** works as an assistant professor and the head of the computer engineering department at Istanbul Medipol University, Turkey. From 2007 to 2012, he worked as an expert researcher at NICT, Japan. He served as a co-editor and secretary for 802.15 TG3c and contributed to many standardization projects, including 802.22, 802.11af, and 1900.7. He is the vice director of the Centre of Excellence in Optical Wireless Communication Technologies (OKATEM) and the vice chair of 802.19 Wireless Coexistence Working Group. He contributed to the technical requirements document and the channel models of 802.15.7r1 standardization, which will enable visible light communication.



**Hasari Celebi** received his BS degree from the Department of Electronics and Communications Engineering at Yildiz Technical University, Istanbul, Turkey, and his MS degree from the Department of Electrical Engineering at the San Jose State University, California. He received his PhD degree from the Department of Electrical Engineering at the University of South Florida, Tampa, Florida, in 2008. He is currently an associate professor in the Department of Engineering at Gebze Technical University, Turkey, and is also the Director of the Institute of Information Technologies, Gebze Technical University. Prior to this, he was with Texas A&M University at Qatar (TAMUQ), Doha, as a research scientist. He received The Research Fellow Excellence Award at TAMUQ in 2010. He was also the recipient of The Best Paper Award at the CrownCom 2009 Conference. His research areas include statistical signal processing, estimation theory, localization, frequency diversity and multiplexing, and cognitive radio.



**Yeon Ho Chung** received his BEng degree in electronic engineering from Kyungpook National University, Daegu, South Korea, in 1984, his MSc degree in communications and signal processing from Imperial College London, UK, in 1992, and his PhD degree in electrical engineering and electronics from the University of Liverpool, UK, in 1996. He was employed as a technical consultant for Freshfield Communications Ltd, UK, in 1994, in the field of the design of mobile radio networks. He has now been working as a professor at the Department of Information and Communications Engineering, Pukyong





**Çağatay Edemen** has received his BSc degree from Marmara University, Istanbul, Turkey, and his PhD degree from Işık University, Istanbul, Turkey, in electronics engineering. He is currently an academic faculty member at Ozyegin University, Istanbul, Turkey. He has been working on several research projects with a focus on information and communication theory and networks in wireless systems.

Another field of interest is optical communication. In particular, he is interested in the applications of visible light communication. He also worked in applied research projects which focused on new generation mobile technology in two pioneer Turkish mobile network operators, Turkcell and Türk Telekom. The main objective of these projects was to contribute to the standards IEEE 802.16m and 3GPP LTE. Dr. Edemen was awarded the IEEE WCNC 2008 Best Paper Award for his work titled "Achievable Rates for the Three User Cooperative Multiple Access Channel."



**Manuel Faria** recently graduated with a master's degree in electrical and computer engineering, the main area of telecommunications, at the Instituto Superior Técnico, Lisbon, Portugal. He deepened his knowledge in optical wireless communications in his master's thesis, which was themed on "transdermal optical communications."



**Gábor Fekete** received his BSc degree in electrical engineering from the Budapest University of Technology and Economics, Hungary, in 2011, and his MSc degree from the same university in 2013. He is currently pursuing his PhD degree in electrical engineering from the Department of Broadband Infocommunications and Electromagnetic Theory at the Budapest University of

Technology and Economics. His research interests cover indoor visible light communication systems, optically generated millimeter-wave, and optical OFDM modulation.



**Mónica Figueiredo** concluded her PhD study in electrical engineering at the University of Aveiro, Portugal, in 2012. She started her research activities in 2001 at the Telecommunications Institute as a collaborator in the group of Integrated Circuits. Currently, she is a researcher in the same group and an assistant professor at the Polytechnic Institute of Leiria, Portugal. Her current main research interests include the design of communication circuits and systems in programmable logic devices, clock distribution and

alignment techniques, synchronization, timing circuits, and high-speed integrated electronics.



**Chadi J. Gabriel** received his PhD degree in physics and materials science at Aix-Marseille University, Marseille, France, in 2013. His work focused on underwater sensor networks, wireless optical communication, performance analysis over fading channels, and modulation and coding techniques. Currently, he is working as an expert signal processing researcher at Netatmo Co. in Boulogne-Billancourt, France.



**Paul Anthony Haigh** received his BEng and PhD degrees from Northumbria University, Newcastle upon Tyne, UK, in 2010 and 2014, respectively. Between 2011 and 2012, Dr. Haigh was awarded the prestigious Marie Curie Fellowship at the European Fellowship for Nuclear Research (CERN) at the youngest age in the history of the organization. His work at CERN focused on the design and testing of radiation-hard high-speed transmitter optical subassemblies for the ATLAS and CMS. During his PhD, Dr. Haigh invented the topic of organic small molecule and polymer visible light communications. He managed to improve data rates in ultralow organic photonic devices from kb/s up to 55 Mb/s. He joined the High Performance Networks Group at the University of Bristol as a research associate in December 2014. His research interests are reconfigurable and agile interfaces between networks. Over the last 4 years, he has published more than 40 refereed journal articles and conference papers.



**Matěj Komanec** is a research assistant at the Faculty of Electrical Engineering of the Czech Technical University in Prague. He received his MS and PhD degrees in radio-electronics from the Czech Technical University in Prague in 2009 and 2014, respectively. His current research interests include specialty optical fibers, free-space optics, visiblelight communication, optical interconnects, and fiber sensing. He is a member of OSA and SPIE.



**Ivan Kudláček** received his MSc degree in electrical engineering and his PhD degree from the Department of Electrotechnology, Faculty of Electrical Engineering, Czech Technical University in Prague (CTU in Prague). He is currently an associate professor and a senior researcher with the Department of Electrotechnology, CTU in Prague. His current research interests are the reliability of electronics devices and ecology electrical equipment.



**Thomas D. C. Little** received his BS degree in biomedical engineering from Rensselaer Polytechnic Institute, Troy, New York, in 1983, and his MS degree in electrical engineering and PhD degree in computer engineering from Syracuse University, New York, in 1989 and 1991, respectively. Currently, he is a professor at the Department of Electrical and Computer Engineering in Boston University, Massachusetts. He is also an associate dean for educational initiatives for the college and serves as an associate director of the National Science Foundation Center for Lighting Enabled Systems and Applications (LESA), formerly known as the Smart Lighting Engineering Research Center, a collaboration of Rensselaer Polytechnic Institute, the University of New Mexico, and Boston University. His recent efforts address research in pervasive computing using wireless technologies. This includes video streaming, optical communications with the visible spectrum, and applications related to ecological sensing, vehicular networks, and wireless healthcare. He is a senior member of the IEEE, a member of the IEEE Computer and Communications Societies, and a member of the Association for Computing Machinery.



**Nuno Lourenço** graduated with an MSc degree in electronics and telecommunications from the University of Aveiro, Portugal, in 2010. He then joined the Instituto de Telecomunicações, Aveiro, participating in several R&D activities in the areas of visible light communication, intelligent LED lighting systems, and wireless sensor networks. In 2013, he joined the Zumtobel Group, in the Austrian city of Dornbirn, initially as a project leader in hardware pre-development, and later as a technology scout/expert in the fields of networks and communications. In 2015, he became a consultant, continuing in his line work of analyzing and evaluating the latest developments of the networking world and their potential benefits to the lighting and automation industries. He currently provides support to multiple R&D activities, also including supervision of MSc candidate students, in the topics of indoor location, sensor network architectures for smart lighting, building automation, and visible light communications.



**Jose M. Luna-Rivera** received his BS and MEng degrees in electronics engineering from the Autonomous University of San Luis Potosi, Mexico, in 1997 and 1998, respectively. He received his PhD degree in electrical engineering from the University of Edinburgh, UK, in 2003. He is currently an associate professor at the College of Sciences at the Autonomous University of San Luis Potosi. His research focuses on signal processing for wireless communication and visible light communications.



**Pengfei Luo** received his BEng degree in communication engineering from Beihua University, China, in 2007, and his joint MSc–PhD degree in optical communications engineering from Beijing University of Posts and Telecommunications, China, in 2013. He was a research fellow of the Department of Physics and Electrical Engineering, Northumbria University, Newcastle upon

Tyne, UK, from December 2013 to October 2014, and a project assistant at Beijing University of Posts and Telecommunications from November 2014 to March 2016. He now works in the Research Department of HiSilicon, Huawei Technologies Co., Ltd, Beijing, China.



**Hoa Le Minh** received his BEng degree in telecommunications from Ho Chi Minh University of Technology, Vietnam, in 1999, his MSc degree in communications engineering from Munich University of Technology, Germany, in 2003, and obtained his PhD degree in optical communications from Northumbria University, Newcastle upon Tyne, UK, in 2007. Prior to joining

Northumbria University as a senior lecturer in 2010 and subsequently the program leader of BEng (Hons) Electrical and Electronic Engineering (2013), he was a research fellow at the Department of Engineering Science and a tutor at St Edmund Hall College, University of Oxford, UK (2007–2010). He worked at R&D Siemens AG, Munich, Germany (2002–2004), as a research assistant in ultrahigh-speed optical communications networks.

Dr. Hoa's expertise is in communications engineering including photonics systems, the emerging inorganic and organic visible light communications technology, smartphone technology, and intelligent mobile ad hoc networks. He has published over 100 journal articles, conference papers, and book chapters.



**Rafael Pérez Jiménez** received his MS degree in 1991 from Universidad Politécnica de Madrid, Spain, and his PhD degree (Hons) in 1995 from Universidad de Las Palmas de Gran Canaria, Spain. He is a full professor at the ULPGC, where he leads the IDeTIC Research Institute. His current research interests are in the field of optical indoor channel characterization and the design of robust

visible light systems for indoor communications, specially applied for sensor interconnection and positioning. He has been awarded with the Gran Canaria Science Prize (2007) and the Vodaphone Foundation Research Award (2010).



**Luís M. Pessoa** graduated and obtained his PhD degree, both in electrical and computer engineering, from the Faculty of Engineering of the University of Porto (FEUP), Portugal, in 2006 and 2011, respectively. He is currently a senior researcher at INESC TEC, mainly involved in the conception and management of R&D projects, coordination of research students, and fostering the valorization

of research results through new contracts with the industry. He has collaborated in several national and international projects in the areas of optical communications and microwave systems. His research interests include digital signal processing using advanced modulation formats, fiber-supported microwave systems, RF/microwave devices, antennas and propagation, and underwater wireless power/communications.



**Wasiu O. Popoola** received a first class (Hons.) degree in electronic and electrical engineering from Obafemi Awolowo University, Nigeria, and his MSc and PhD degrees from Northumbria University at Newcastle upon Tyne, UK. During his PhD, he was awarded the Xcel Best Engineering and Technology Student of the Year 2009.

He is currently a chancellor's fellow at the Institute for Digital Communications, University of Edinburgh, UK. Previously, he was a lecturer in electronic engineering at Glasgow Caledonian University, UK, between August 2012 and December 2014. He has published well over 70 journal articles/conference papers/patents, and a number of those are invited papers; see <http://goo.gl/JdCo3R>. He was an invited speaker at the 2016 IEEE Photonics Society Summer Topicals. He coauthored the book *Optical Wireless Communications: System and Channel Modelling with MATLAB®*, published by CRC Press in 2012. His research interests include optical (wireless and fiber) and digital communications.



**Jose A. Rabadan-Borges** received his MS and PhD (Hons) degrees from the Universidad de Las Palmas de Gran Canaria, Spain, in 1995 and 2000, respectively. Currently, he is an assistant professor at the ULPGC. His research interests are in the field of the wireless infrared communications for both wideband local area networks and narrowband sensors networks, high-performance modulation and codifi-

cations schemes for VLC communications, and indoor VLC channel characterization.



**Michael B. Rahaim** is a postdoctoral researcher in the Department of Electrical and Computer Engineering at Boston University, Massachusetts, working with the National Science Foundation Center for Lighting Enabled Systems and Applications (LESA). His research focuses on software-defined radio, visible light communication, heterogeneous networks, and smart lighting. He received

his BS degree in electrical and computer systems engineering from Rensselaer Polytechnic Institute, Troy, New York, in 2007, and his MS and PhD degrees in computer engineering from Boston University in 2011 and 2015, respectively.



**Sujan Rajbhandari** obtained his BEng degree in electronics and communication engineering from the Institute of Engineering, Nepal, in 2004. He obtained his MSc and PhD degrees from Northumbria University, Newcastle upon Tyne, UK, in 2006 and 2010, respectively. He was awarded the P.O. Byrne prize for his MSc project. He worked at Northumbria University from 2009 to 2012 as a

senior research assistant and research fellow. He then joined the University of Oxford, UK, as a postdoctorate research assistant in December 2012 and worked in EPSRC's Ultra-Parallel Visible Light Communications (UP-VLC) project. He is currently working as a lecturer at the School of Computing, Engineering and Mathematics, Coventry University, UK. Dr. Rajbhandari has published more than 100 scholarly articles and is a coauthor of the book *Optical Wireless Communications: Systems and Channel Modelling with MATLAB®*. He was an invited speaker in Information and Communication Technology Forum 2015 at Manchester. He has also served as a local organizing and technical program committee member for a number of conferences and proceeding editor for EFEA 2012 and NOC/OC&I 2011. He is a regular reviewer for several publications including the IEEE, OSA, and IET journals. His research interests lie in the area of optical communications and signal processing. He is a member of IEEE.



**Carlos Ribeiro** received his BSc degree (5-year course) in electronic engineering from the University of Coimbra, Portugal, in 1996. In 2003, he received his MSc degree in electronics and computer engineering from the same university. In 2010, he received his PhD degree in electronics engineering from the University of Aveiro, Portugal. In 1997, he joined the Department of Electronics of the Polytechnic Institute of Leiria, Portugal,

where he is currently an assistant professor. He is a researcher in signal processing for communications. His main research topics are PHY algorithms for RF and VLC communication systems and its implementation.

He has published tens of research articles and conference papers in international journals. He has been participating in several national and European projects.



**Luis Rodrigues** graduated with his MSc degree in electronic and telecommunications engineering from the University of Aveiro, Portugal, and he is currently in the MAP-tele PhD program. His master's thesis theme was Error Correcting Codes for Visible Light Communications, aiming performance improvements of OFDM-based VLC systems using an FPGA. He is currently working with analog LED drivers and optical receivers.



**Julio F. Rufo Torres** received his MS and PhD degrees from the Universidad de Las Palmas de Gran Canaria, Spain, in 2008 and 2016, respectively. His current research interests are in the field of visual light communications systems for indoor communications applied to sensor networks and Internet of things.



**Elham Sarbazi** received her BSc degree in electrical and computer engineering from the University of Tehran, Iran, in 2011, and her MSc degree (first class honors) on communication systems from the Department of Electrical and Electronics Engineering, Ozyegin University, Istanbul, Turkey, in 2014. She is currently working toward her PhD degree under the supervision of Prof. Harald Haas at the Institute for Digital Communications, University of Edinburgh, Edinburgh, UK. Her research interests mainly include optical wireless communications and visible light communications.



**Paulo Sérgio de Brito André** received his bachelor's degree in physics engineering, PhD degree in physics, and Agregação title (habilitation) degree from the Universidade de Aveiro, Portugal, in 1996, 2002, and 2011, respectively. In 2013, he joined as an associate professor at the Instituto Superior Técnico, University of Lisbon, Portugal, lecturing courses on telecommunications. Since 2015, he has been a vice director of the Department of Electrical and Computer Engineering. His current research interests include the study and simulation of photonic and optoelectronic components, optical sensors, optical communications systems, and networks.



**Parvaneh Shams** received her BSc degree in computer engineering from the University of Tabriz, Iran, in 2004, and her MSc degree in electronics and communication engineering from the Iran University of Science and Technology, Tehran, in 2012. Her research interests include optical wireless communications and visible light communications, mainly Mac layer protocol performance. She is currently a PhD student in communication engineering under the supervision of Prof. Niyazi Odabaşoğlu at Istanbul University, Turkey.



**Martin Siegel** studied physics and received his diploma from the University Heidelberg, Germany, in 2005 and his PhD degree from the University of Hannover, Germany, in 2009. From 2010 to 2011, he worked at High Q Laser GmbH in Austria, where he was responsible for the development of a pulsed laser system. In 2011, he began working as a technology scout for the Zumtobel Group, identifying and evaluating new technological developments. Since 2016, he has been the Director of Research and Pre-Development at the Zumtobel corporate headquarters in Dornbirn. He has published a number of scientific publications and has presented papers in numerous conferences worldwide. Topics of interest range from lighting and smart-lighting applications all the way to sensor technology and laser development.



**Bernardo Silva** obtained his MSc degree in electrical and computer engineering from the Faculty of Engineering at the University of Porto (FEUP), Portugal, in 2015. He majored in automation and control, with the specialization in robotics and systems, and minored in enterprise information systems, licensing projects, and electrical design in industrial installations. His final dissertation project was “Underwater Optical Communication: An Approach Based On LED,” under the supervision of Prof. Nuno Cruz and Dr. Luís Pessoa. His fields of interest include programming, economics and management, applied electronics, acquisition and signal processing, industrial informatics, and industrial robotics.



**Hsin-Mu (Michael) Tsai** is an associate professor in the Department of Computer Science and Information Engineering and Graduate Institute of Networking and Multimedia at National Taiwan University, Taipei. He received his BSE in computer science and information engineering from National Taiwan University in 2002 and his MS and PhD degrees in electrical and computer engineering from



Carnegie Mellon University, Pittsburgh, Pennsylvania, in 2006 and 2010, respectively. Dr. Tsai's recognitions include the 2015 K. T. Li Young Researcher Award, 2014 Intel Labs Distinguished Collaborative Research Award, 2013 Intel Early Career Faculty Award (first recipient outside of North America and Europe), and National Taiwan University's Distinguished Teaching Award. Dr. Tsai served as one of the founding workshop co-chairs for the first ACM Visible Light Communication System (VLCS) Workshop in 2014, and TPC co-chair for IEEE VNC 2016 and ACM VANET 2013. His research interests include vehicular networking and communications, wireless channel and link measurements, vehicle safety systems, and visible light communications.



**Xuan Tang** is a principal investigator and an associate professor at the Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, since October 2014. She obtained her BEng (first class with honors) degree in electronic and communications engineering in 2008 and her PhD degree from Northumbria University, Newcastle upon Tyne, UK, in 2013. From October 2012 to July 2014, Dr. Tang worked as a post-doctoral researcher at the Department of Electronic Communications Engineering, Tsinghua University, Beijing, China, and then joined the National Basic Research Program of China (973 Program) as the key researcher. From October 2013 to April 2014, she was the visiting academic at the University of Science and Technology of China, Hefei. She has received funding from the China Postdoctoral Science Foundation and National Science Fund for Young Scholars. She has published 40 articles and is an IEEE member. Her research interests are in the areas of optical wireless communications including high-speed infrared/ultra-violet laser communications, visible light communications and optical MIMO systems, and radio frequency communication technologies.



**Eszter Udvarý** received her PhD degree in electrical engineering from Budapest University of Technology and Economics, Hungary, in 2009. She is currently an associate professor at the Department of Broadband Infocommunications and Electromagnetic Theory, Budapest University of Technology and Economics, where she leads the Optical and Microwave Telecommunication Lab. She currently teaches courses on optical communication devices and networks. Dr. Udvarý's research interests are in the broad areas of optical communications, including optical and microwave communication systems, radio over fiber systems, optical and microwave interactions, and applications of special electro-optical devices. Her special research focuses on multifunctional