Guest Editorial Latest Advances in Optical Networks for 5G Communications and Beyond

Massimo Tornatore, *Senior Member, IEEE*, Elaine Wong, *Senior Member, IEEE*, Zuqing Zhu, *Senior Member, IEEE*, Ramon Casellas, *Senior Member, IEEE*, Balagangadhar G. Bathula, *Member, IEEE*, and Lena Wosinska, *Senior Member, IEEE*

***Abstract*— This Special Issue contains a collection of outstanding papers covering several recent advances in optical networks for 5G communications and beyond. Papers are organized into four categories: network resource planning; optical access networks; optical fronthaul solutions; and autonomous and data-driven network management. In this introduction, a brief overview of the field is given, followed by a summary of the seventeen papers of this Special Issue, and a discussion of future directions in the field.**

***Index Terms*— Optical networks, machine learning, fronthaul, telemetry, free space optics, physical layer security, software-defined networking (SDN), network functions virtualization (NFV).**

I. On the Special Issue

THIS Special Issue (SI) features the latest research contributions investigating advances in optical networks enabling 5G communications and beyond. The new aggressive requirements brought on by emerging services and an increasing number of connected users and devices are shaping the evolution not only of the wireless/radio segment but also of the higher-tier optical wired segments, spanning from access through to the backbone and core. Optical networks are already evolving from rigid infrastructures, simply designed to collect and transfer aggregated traffic, to a composite network-and-computing ecosystem, that is flexible and resource efficient thanks to the adoption of network automation, flexible grid equipment, and coherent transmission.

On a long-term research horizon, pointing towards beyond 5G (or 6G) communications, new challenging technical directions are arising which promise to revolutionize user's network experience (to name a few, multi-sensorial and holographic communication, pervasive machine learning, cell-free communication, coordination of heterogeneous wireless access technologies, and quantum communication). While this is a vision and the exact definitions of the new services have yet to be clearly identified, future service requirements are expected to be further exacerbated in terms of capacity, latency, reconfigurability, reliability, and security.

Hence, simply scaling up the present mode of operation in optical networks is not an option. A redesign with new optical networks that feature in-built physical security, sub-linear bandwidth scaling costs, extreme low-latency, and reconfigurability will be needed. New, possibly disruptive, solutions in the field of optical networking and communication must be investigated, both at the data plane and at the control plane. While the impact of these 5G and beyond requirements on the wireless front-end has been the subject of intensive investigations, research addressing their impact on the optical network is still lagging behind. Hence, we believed it was imperative to announce an IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (JSAC) SI to stimulate a more thorough investigation of new research directions on optical networking and communication.

The call attracted topics ranging from pure physical-layer analysis to network optimization and automation. Some of the contributions present a clear industrial footprint, while some other papers explore more theoretical aspects, enriching the SI with a nice blend of several perspectives.

II. Summary of the Accepted Articles

The 17 accepted articles have been classified into four categories: 1) network resource planning; 2) optical access networks; 3) optical fronthaul solutions; and 4) autonomous and data-driven network management.

A. Network Resource Planning

Several novel directions for network planning are covered in this SI. To deal with the increasing threats that natural and man-made disasters pose to optical networks, in the article "Probabilistic shared risk link groups modeling correlated resource failures caused by disasters" [item 1) in the

Massimo Tornatore is with the Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milan, Italy (e-mail: massimo.tornatore@polimi.it).

Elaine Wong is with the Department of Electrical and Electronic Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia (e-mail: ewon@unimelb.edu.au).

Zuqing Zhu is with the School of Information Science and Technology, University of Science and Technology of China, Hefei 230027, Anhui, China (e-mail: zqzhu@ieee.org).

Ramon Casellas is with the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), 08860 Castelldefels, Spain (e-mail: ramon.casellas@cttc.es).

Balagangadhar G. Bathula is with Network Core and Infrastructure Services, AT&T Labs, Middletown, NJ 07748 USA (e-mail: bb4341@att.com).

Lena Wosinska is with the Department of Electrical Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden (e-mail: wosinska@chalmers.se).

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Appendix], the authors introduce novel stochastic models to evaluate the impact of large-scale failures on optical backbones and propose an extension of the concept of shared risk link group in this context. In the article "Resource allocation in space division multiplexed elastic optical networks secured with quantum key distribution" [item 2) in the Appendix], the authors investigate how to jointly allocate quantum key distribution (QKD) channels and conventional data channels in space-division multiplexed (SDM) optical networks. QKD is definitely an emerging topic, and also the article "Hybrid trusted/untrusted relay based quantum key distribution over optical backbone networks" [item 3) in the Appendix] studies this topic, focusing on how to integrate trusted and untrusted relays in optical backbones. SDM is also investigated in "Proactive fragmentation management scheme based on crosstalk-avoided batch processing for spectrally-spatially elastic optical networks" [item 4) in the Appendix], where crosstalk considerations are leveraged during defragmentation. Finally, papers "Disruption Minimized Bandwidth Scaling in EON-enabled Transport Network Slices" [item 5) in the Appendix] and "Highly-Efficient Switch Migration for Controller Load Balancing in Elastic Optical Inter-Datacenter Networks" [item 6) in the Appendix] focus on emerging network management problems in the context of slicing and controller migration in elastic optical networks.

B. Optical Access Networks

The access segment will have a dominant contribution to the energy consumption of future networks. The articles "Energy-and bandwidth-efficient, QoS-aware edge caching in fog-enhanced radio access networks" [item 7) in the Appendix] and "SDN-enabled resource management for converged Fi-Wi 5G fronthaul" [item 8) in the Appendix] offer novel models and resource allocation schemes for energy minimization in next-generation converged access networks. Another key challenge is related to scalable support for fronthauling of massive data flows coming from 5G and beyond antennas. In this direction, the articles "Wavelength division multiplexed radio over fiber links for 5G fronthaul networks" [item 9) in the Appendix] and "Experimental demonstration of extended 5G digital fronthaul over a partially-disaggregated WDM/SDM network" [item 10) in the Appendix] explore novel system architectures for optical fronthaul based on wavelength division multiplexing (WDM) and joint SDM-WDM, respectively.

C. Optical Fronthaul Solutions

Novel transmission technologies are being investigated to provide, as already mentioned, low-cost and scalable fronthaul solutions. In the article "Reconfigurable fiber wireless IFoF fronthaul with 60 GHz phased array antenna and silicon photonic ROADM for 5G mmWave C-RANs" [item 11) in the Appendix], the authors experimentally demonstrate a bandwidth-reconfigurable mm-wave fiber wireless (FiWi) fronthaul bus topology for 5G centralized-radio access networks (C-RAN), providing a path toward flexible and reconfigurable 5G C-RANs. In the article "Analogue coherent-optical mobile fronthaul with integrated photonic beamforming" [item 12) in the Appendix], the authors experimentally demonstrate a mobile fronthaul methodology using analog coherent optical transmission of native radio signals. The tunability of electro-absorption modulated lasers used as analog coherent optical homodyne detectors is shown to support true-time delay functionality for beam-steering phased-array antennas. In the article "Quad-mode VCSEL optical carrier for long-reach Ka-band millimeter-wave over fiber link" [item 13) in the Appendix], the authors demonstrate the establishment of a long-reach mm-wave over fiber (MMWoF) link, in which one mode of the quad-mode optical carriers is modulated by 16-QAM OFDM data stream to achieve an optical single-carrier modulation.

D. Autonomous and Data-Driven Network Management

Network automation based on a novel data-driven machine-learning solution is penetrating all network segments, and management in optical networks, in particular, is now the subject of intense innovation. The article "Latency-sensitive edge/cloud serverless dynamic deployment over telemetry-based packet-optical network" [item 14) in the Appendix] investigates the automated deployment and reconfiguration of serverless functions in edge/cloud systems, offering an experimental demonstration of these functions. In the article "Autonomous and energy efficient lightpath operation based on digital subcarrier multiplexing" [item 15) in the Appendix], the authors offer several new guidelines on how to achieve autonomous operation of Digital Subcarrier Multiplexing (DSCM) systems for optical transmission. The article "A multi-task-learning-based transfer deep reinforcement learning design for autonomic optical networks" [item 16) in the Appendix] proposes to use transfer learning (across different networks) for scalable and generalizable application of Deep Reinforcement Learning in the solution of routing, modulation, and spectrum assignment. Extending the application to wireless optical systems, the article "Invoking deep learning for joint estimation of indoor LiFi user position and orientation" [item 17) in the Appendix] proposes to use artificial neural networks (ANNs) to jointly estimate the user 3-D position and user equipment orientation in indoor LiFi systems.

III. Conclusion and Future Directions

Optical networks are massively-deployed, critical communication infrastructures that form the physical backbone of today's Internet. To cope with an incessant traffic increase and to comply with new emerging requirements in terms of energy consumption and reliability, optical networks are constantly evolving, supported, and stimulated by a very active industrial and academic research ecosystem.

The articles of this Special Issue provide substantial contributions in the areas of network resource planning, access and fronthaul solutions, and autonomous network management, as discussed in the previous section. Still, research for new optical-network solutions in the context of future 5G and beyond communications is a very active and emerging area, and a variety of challenges exist which still have to be addressed, as discussed below.

A. Low-Margin Design and Multi-Band Optical Networks

Several core and metro optical-network deployments are currently reaching *C*-band spectrum saturation, and the installation/lighting-up of new fibers might be cost-prohibitive. Low-margin optical-network design and multi-band optical networks are two rising research directions in this area. The low-margin design aims at removing traditional design margin (that can be of several dBs), by leveraging more advanced transmission techniques (as probabilistic constellation shaping), and by deriving more accurate device characterizations, typically through monitored data (such as elaborated using machine learning). Instead, multi-band networks exploit unconventional fiber bands (such as *E*-, *S*-, and *L*-band) beyond *C*-band to upgrade network capacity and postpone installation of new fiber. In multi-band networks, several challenges related to both physical-layer modeling and network resource allocation still need to be addressed. Another trend that is gaining traction is the adoption of high-speed pluggable optical transceivers, such as 400 and 800 ZR, characterized by lower cost and shorter reaches compared to conventional coherent transceivers. To support these very high bit rates, research on higher baud-rate coherent optics, including 128, 140, and 200 GBd, will be needed, both in terms of device design and characterization, and in terms of network architectures and planning.

B. Physical-Layer Security

In light of the critical role that optical networks have in our society, new methods to enhance communication security at the optical layer have also to be investigated, and new techniques for physical-layer attack detection and mitigation need to be developed. In this context, quantum communications represent an innovative and rich research area. Quantum-based security techniques are still far from massive deployment due to multiple limitations, such as low key rate, lack of telecom compatibility, and absence of proper mechanisms to maintain services running in presence of physical-layer attacks. Moreover, new optical-network solutions, where quantum channels co-exist with data channel, need to be devised.

C. Disaggregation and Softwarization

Another trend and research direction are related to the (partial) disaggregation and softwarization of optical networks, such as the decoupling of the terminal devices (such as the transponders) from the rest of the line system, and the critical implications that such decoupling has in terms of control and management. In this scenario, the concept of "open networking" is attracting wide consensus. Open optical networking requires interface interoperability (typically not ensured in current deployments) and, hence, the design of new hardware and software supporting this interoperability. New and/or refined architectures for open optical networks are needed, including new device and service modeling, as well as more standard and interoperable ways to model physical impairments. Moreover, the softwarization of optical networks can leverage new technologies, such as software-defined networking (SDN) and network functions virtualization (NFV), to redefine the procedure of network control and management. Hence, optical networks can become more flexible, programmable, and application-aware to enable service providers to deliver short time-to-market, elastic, and cost-effective services and solutions. Finally, the importance of streaming telemetry cannot be overstated. In addition to common uses such as alarm or fault management, efficient protocols and systems are required to make use of such high volumes of data, with the ultimate goal of enabling advanced network automation. Further research is required beyond existing basic "expert systems" or more complex reinforcement learning approaches.

D. Access Automation and Virtualization for Enterprise 5G

Another area of high interest lies in the so-called "enterprise 5G," which promises to fuel new services at higher data rates, increased network capacity, and improved security indoors. In fact, ultra-high capacity indoor wireless connectivity is considered a key technology to support end-to-end delivery in the beyond-5G and 6G era. New network architectures that harness high-capacity optical fiber distribution networks along with resource sharing and interoperability between 5G and existing wireless LAN technologies, such as Wi-Fi and Wi-Fi 6, will be key focus research areas. With this in mind, new solutions in the optical access segment will be needed, both in terms of the physical infrastructure and of the control plane. In particular, emerging services characterized by challenging latency, capacity, and reliability requirements will lead to densification of the radio access network, which, in turn, will pose several challenges for optical access networks. In terms of physical infrastructure, further densification of the fiber network and convergence of optical and wireless access networks are expected. Hence, a novel solution to further improve cost and energy efficiency will be an important research topic. To meet latency requirements, requests will need to be served close to users leading to a more distributed (and virtualized) cloud ("fog") access network, where the networking and computing segments will be jointly designed. Access network automation will be the key enabler to improve user experience, operational cost, and energy efficiency.

E. Data-Center Interconnection

The attention on enterprise 5G will also bring research interests to data-center interconnections (DCIs) because data-centers (DCs) are indispensable facilities for many 5G-based network services. The geographically distributed DCs in a DCI can help service providers to improve their performance on service coverage, latency, and availability. Optical networking plays an important role in DCIs. With the advances on flexible-grid elastic optical networking, the conventional packet-switched architecture for DCIs might be evolved to an optical-circuit-switched one for better scalability and cost-effectiveness. Meanwhile, how to orchestrate the IT and bandwidth resources in an optical DCI to effectively support the deployment of NFV-based services is also an interesting research topic in this area.

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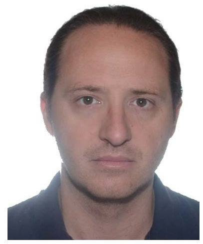
Appendix
Related Works

1) B. Vass *et al.*, "Probabilistic shared risk link groups modeling correlated resource failures caused by disasters," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064652.
2) E. E. Moghaddam, H. Beyranvand, and J. A. Salehi, "Resource allocation in space division multiplexed elastic optical networks secured with quantum key distribution," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064641.
3) Y. Cao, Y. Zhao, J. Li, R. Lin, J. Zhang, and J. Chen, "Hybrid trusted/untrusted relay based quantum key distribution over optical backbone networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064662.
4) B. C. Chatterjee, A. Wadud, and E. Oki, "Proactive fragmentation management scheme based on crosstalk-avoided batch processing for spectrally-spatially elastic optical networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064594.
5) N. Shahriar *et al.*, "Disruption minimized bandwidth scaling in EON-enabled transport network slices," *IEEE J. Sel. Areas Commun.*, early access, Mar. 10, 2021, doi: 10.1109/JSAC.2021.3064643.
6) Y. Liu, H. Gu, F. Yan, and N. Calabretta, "Highly-efficient switch migration for controller load balancing in elastic optical inter-datacenter networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 11, 2021, doi: 10.1109/JSAC.2021.3064664.
7) C. Bhar and E. Agrell, "Energy-and bandwidth-efficient, QoS-aware edge caching in fog-enhanced radio access networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064659.
8) E. Datsika *et al.*, "SDN-enabled resource management for converged Fi-Wi 5G fronthaul," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064651.
9) G. Pandey, A. Choudhary, and A. Dixit, "Wavelength division multiplexed radio over fiber links for 5G fronthaul networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064654.
10) J. M. Fabrega *et al.*, "Experimental demonstration of extended 5G digital fronthaul over a partially-disaggregated WDM/SDM network," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064645.
11) A. Tsakyridis *et al.*, "Reconfigurable fiber wireless IFoF fronthaul with 60 GHz phased array antenna and silicon photonic ROADM for 5G mmWave C-RANs," *IEEE J. Sel. Areas Commun.*, early access, Mar. 10, 2021 , doi: 10.1109/JSAC.2021.3064649.
12) D. Milovancev, N. Vokic, D. Loschenbrand, T. Zemen, and B. Schrenk, "Analogue coherent-optical mobile fronthaul with integrated photonic beamforming," *IEEE J. Sel. Areas Commun.*, early access, Apr. 5, 2021, doi: 10.1109/JSAC.2021.3064640.
13) C.-T. Tsai, H.-Y. Wang, Y.-C. Chi, C.-H. Cheng, and G.-R. Lin, "Quad-mode VCSEL optical carrier for long-reach Ka-band millimeter-wave over fiber link," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064644.
14) I. Pelle, F. Paolucci, B. Sonkoly, and F. Cugini, "Latency-sensitive Edge/Cloud serverless dynamic deployment over telemetry-based packet-optical network," *IEEE J. Sel. Areas Commun.*, early access, Mar. 10, 2021, doi: 10.1109/JSAC.2021.3064655.
15) L. Velasco *et al.*, "Autonomous and energy efficient lightpath operation based on digital subcarrier multiplexing," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064698.
16) X. Chen, R. Proietti, C.-Y. Liu, and S. J. B. Yoo, "A multi-task-learning-based transfer deep reinforcement learning design for autonomic optical networks," *IEEE J. Sel. Areas Commun.*, early access, Mar. 9, 2021, doi: 10.1109/JSAC.2021.3064657.
17) M. A. Arfaoui *et al.*, "Invoking deep learning for joint estimation of indoor LiFi user position and orientation," *IEEE J. Sel. Areas Commun.*, early access, Mar. 10, 2021, doi: 10.1109/JSAC.2021.3064637.



Massimo Tornatore (Senior Member, IEEE) received the Ph.D. degree from the Politecnico di Milano in 2006. He is currently an Associate Professor with the Politecnico di Milano. He also holds an appointment as an Adjunct Professor with the University of California, Davis, USA, and a Visiting Professor with the University of Waterloo, Canada. His research interests include performance evaluation and optimization of communication networks (with an emphasis on optical networking), cloud computing, and machine learning application for network management. In these areas, he has coauthored more than 400 peer-reviewed conference and journal papers (with 18 best paper awards), two books, and one patent. He is a member of the Editorial Board of, among others, IEEE Communications Surveys & Tutorials, IEEE Transactions on Network and Service Management, and IEEE Communications Letters.

Elaine Wong (Senior Member, IEEE) received the B.Eng. degree in electrical engineering and the Ph.D. degree from The University of Melbourne, Australia, in 1997 and 2002, respectively. She is currently an Associate Dean and a Professor with the Faculty of Engineering and Information Technology, The University of Melbourne. She has made numerous significant intellectual contributions in the field of optical fiber communications and optical networking, particularly in the areas of optical access network architectures and subsystem technologies, energy-efficient networking and subsystem technologies, converged/hybrid fiber-wireless networks and subsystem technologies, and more recently in low-latency human-to-machine communications in the tactile internet and 5G and beyond networks. She is a fellow of OSA. She was previously an Associate Editor of IEEE/OSA Journal of Optical Communications and Networking and IEEE Journal of Lightwave Technology. She is also the Secretary of the Steering Committee, IEEE Journal of Lightwave Technology, Chair of OFC 2021 Track N4: Optical Access Networks for Fixed and Mobile Services, and the Co-Chair of Optical Networks and Systems (ONS) Symposium of the ICC 2021.

Zuqing Zhu (Senior Member, IEEE) received the Ph.D. degree from the Department of Electrical and Computer Engineering, University of California, Davis, in 2007. From 2007 to 2011, he worked with the Service Provider Technology Group, Cisco Systems, San Jose, CA, USA, as a Software Engineer. In January 2011, he joined the University of Science and Technology of China, where he is currently a Full Professor. He has published more than 200 articles in peer-reviewed journals and conferences. He is a Senior Member of OSA. He has received the Best Paper Award from IEEE ICC 2013, IEEE GLOBECOM 2013, IEEE ICNC 2014, IEEE ICC 2015, and ONDM 2018. He is also an Editorial Board member of *IEEE Communications Magazine*, IEEE Transactions on Network and Service Management, *Optics Express*, and *Optical Switching and Networking*. He was an IEEE Communications Society Distinguished Lecturer from 2018 to 2019.

Ramon Casellas (Senior Member, IEEE) received the Ph.D. degree in telecommunications from the Ecole Nationale Supérieure des Télécommunications (ENST), Paris, in 2002. He worked as an Associate Professor with ENST. In March 2006, he joined the CTTC Optical Networking Area, where he currently holds a Senior Researcher position. His research interest areas include GMPLS/PCE architecture, SDN, NFV, traffic engineering, and distributed control schemes, with applications to optical and disaggregated transport networks. He has coauthored five book chapters, over 200 international and peer-reviewed journal and conference papers, five IETF RFCs in the TEAS, PCE, and CCAMP Working Groups, and several internet drafts. He is an OSA Member and an IEEE ComSoc Instructor on the topic of SDN for Optical Networks. He is also a Contributor of the Open Networking Foundation (ONF) and a member of the Open Disaggregated Transport Networks (ODTN) Project. He has been a TPC Member of IPOP, IEEE SDN/NFV, and GLOBECOM; a recognized Reviewer of IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY and *JOCN* (2014, 1015); a Sub-Committee Member of OSA OFC (N2 and N3) and ECOC (N6); the ONDM 2018 TPC Chair; the ONDM 2020 General Chair; and the OFC 2021 Program Chair. He is also an Associate Editor of the IEEE/OSA JOURNAL OF OPTICAL COMMUNICATIONS AND NETWORKING.

Balagangadhar G. Bathula (Member, IEEE) received the Ph.D. degree in electrical communication engineering from the Indian Institute of Science, Bangalore, India. He is currently working as a Principal Member of the Technical Staff, Network Core Infrastructure and Services, AT&T Labs, USA. Before joining AT&T, he worked as a Postdoctoral Researcher with the Department of Electrical Engineering, Columbia University, New York. He is also leading the activities of Open ROADM Multi-Source Agreement (MSA) (disaggregated transport layer). His research interests are in software-defined networks (SDNs), open architectures for transport, cross-layer network architectures, backbone network design, network cost optimization, optical networks and telemetry, and machine learning. He served as a reviewer for many IEEE/OSA conferences/journals. He has published several articles in the area of optical networks and holds five patents.

Lena Wosinska (Senior Member, IEEE) received the Ph.D. degree in photonics and the Docent degree in optical networks from the KTH Royal Institute of Technology, Sweden. Until October 2018, she was a Full Professor of telecommunication with the KTH Royal Institute of Technology. At KTH, she established a world-leading research group working on optical networks. She is currently a Research Professor with the Chalmers University of Technology, Sweden, where she moved together with her team. She has been working on several EU projects and coordinating a number of national and international research projects. She has been involved in many expert assignments, including serving in the panels evaluating research project proposals for many funding agencies; guest editorships of IEEE, OSA, Elsevier, and Springer journals; serving as the general chair and the Co-Chair of several IEEE, OSA, and SPIE conferences, and workshops. She has been an Associate Editor of *Journal of Optical Networking* (OSA) and IEEE/OSA JOURNAL OF OPTICAL COMMUNICATIONS AND NETWORKING. She is also serving on the Editorial Board of *Photonic Network Communications* journal (Springer) and TRANSACTIONS ON EMERGING TELECOMMUNICATIONS TECHNOLOGIES (Wiley).