Guest Editorial
Ultra Wideband WDM Systems

I. Introduction

APPLICATIONS such as video streaming and cloud computing became part of our daily life. With others, they are considerably contributing to generate the enormous amount of data that is nowadays transmitted over the global optical backbone. IP traffic has been continuously increasing over a decade, with an estimated compound annual growth rate (CAGR) up to ∼35% [1] in 2014, and finally reaching the current ∼26% [2]. The CAGR has been heterogeneous, in some cases – where the broadband penetration has been completed – it shows signs of saturation.

Since ∼10 years, research has been fueled by a possible capacity crunch, with a considerable number of articles claiming that a breakthrough in technology was needed to cope with the exponential increase in bandwidth demand. This led to significant efforts to identify solutions such as multi-core/-mode fibers – to cope with the upcoming scenario. Although the capacity crunch did not happen, the CAGR keeps growing. Consequently, as the aforementioned solutions were not mature, operators relied on the well established C-band technology by deploying – when possible – more fibers.

At the moment, it is difficult to predict for how long the traffic will continue to grow and it is not clear what will happen once technologies such as machine-to-machine, 5G, virtual reality, will finally take off. Operators believe that the data traffic growth – at this pace – will not last forever everywhere. This implies that there will be scenarios where ultra-high capacity will be needed, and others no.

The largest cost of an optical fiber infrastructure is represented by the fiber deployment. This is even more relevant in case there is no space left within the ducts, because the cost of a new overlay is enormous. Given these boundaries conditions – and considering the recent large deployment of ITU-G.652D – the option to exploit the remaining low-loss windows becomes attractive. In particular, in the current scenario of uncertainty, the addition of the neighbour bands to current commercial C-band might provide the required bandwidth for several relevant use cases.

Nowadays, L-band systems are commercial[1] and as discussed in the manuscripts of the special issue, S-band is being largely investigated. The extension of transmission beyond C-band – O, E, S, L, and U – is here denominated as multi-band. This might represent a valid alternative to multi-mode/-core as it owns the considerable advantage of not requiring immediate fiber deployment, and to multi-fiber as dark fibers might not be always available. Moreover, state-of-the-art networks deploying coherent optical technologies can be fully abstracted down to the physical layer and consequently controlled and managed [3]. In this context, the use of multiple bands on each fiber may also enable networking benefits on top of extra transmission capacity.

II. The Contributions to the Special Issue

This special issue includes six invited manuscripts and a regular one. The topics range from network operators perspective to components design and numerical analysis.

The first two manuscripts discusses the optimization and challenges of systems where C and L-band are employed for transmission. In *"Optimized Design and Challenges for C&L Optical Line Systems"* by V. Lopez *et al.*, the authors report on the challenges that network operators encounter because of continuous growth of bandwidth requirements. It highlights the costs of additional fiber deployment and the opportunity to employ now mature C&L technology for an efficient utilization of the existing optical fiber infrastructure. The article concludes with a capacity record of 56.4 Tb/s over 800 km employing commercial C+L-band equipment.

The next article – *"Opportunities and Challenges of C+L Transmission Systems"* by M. Cantono *et al.* – discusses the challenges and opportunities for C+L optical line systems based on the experience of a global Internet service provider in deploying and operating such networks. It deals with technical aspects and describes best practices for designing of C+L links, showing that it is possible to achieve a total system capacity, even larger that 2 × C-band systems.

The next three manuscripts deal with the in-line components for wideband systems.

In *"Recent Advances in 100+nm Ultra-Wideband Fiber-Optic Transmission Systems Using Semiconductor Optical Amplifiers"*, J. Renaudier *et al.* present a comprehensive overview on the potentialities of utilizing a semiconductor optical amplifier (SOA) to build wideband systems beyond 100 nm. SOA possesses the unique property of enabling up to 100 nm continuous amplification, thus becoming a possible solution for enabling wideband systems. The authors review their recent lab and field trial demonstrations with real-time traffic. Reporting transmission up to 107 Tb/s over 300 km of standard single mode fiber (SSMF) using hybrid UWB Raman/SOA technique.

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[1] Although L-band is commercial, the large majority of operating networks is C-band only, and the implication of C+L-band systems, in particular at network management level, are not clear yet.

A fundamental network element for optical communication systems is the reconfigurable optical add and drop multiplexers (ROADM). The fourth paper – *"Wavelength-Division Demultiplexing Enhanced by Silicon-Photonic Tunable Filters in Ultra-Wideband Optical-Path Networks"* by Y. Mori– presents a new architecture which is suitable for wideband systems, where – to cope with the large number of wavelengths– an optical wavelength-tunable filter is placed in front of each receiver. The concept is demonstrated by realizing a flexible signal drop in a C+L-band optical-path network by using an optical wavelength-tunable filter prototype implemented on a single silicon-photonic chip. The tunable filter is experimentally tested with 100/200 QPSK/16QAM signals, by extracting one out of 285 channels within a C+L-band. The net fiber capacity reaches 57 Tb/s. The last component article – *"A study on the Effect of Ultra-wide Band WDM on Optical Transmission Systems"* by S. Okamoto – discusses the technology for a practical implementation of the bands beyond C&L, in terms of amplifiers and demultiplexers, paying attention to the inter-channel interference caused by stimulated Raman scattering (SRS). The authors conducted two experiments. In the first, they utilized components for the five bands (four different doped fiber amplifiers) together with a devised strategy for adaptively allocating channels by considering the wavelength dependence of the optical signal-to-noise ratio. In the second, they investigated the inter-channel interference effect caused by SRS between S- and L-band over 210 km.

The last two manuscripts deal with numerical analyses. The *"On Numerical Simulations of Ultra-Wideband Long-haul Optical Communication Systems"* by P. Serena *et al.* evaluates the reliability of numerical simulations for C+L-band. The authors consider the split-step Fourier method (SSFM) and assess its complexity and feasibility in case of utilization of graphical processing units (GPU), showing that the Manakov equation in the nonlinear step of the SSFM remains a valid solution also for UWB, even though the underlying assumptions may be violated. Last, they proposed a technique – named virtual channel grouping – to speed up SSFM simulations in the UWB regime together with importance sampling-based techniques to accelerate the computation of the enhanced Gaussian noise (EGN) model. The computational times lie in the order of seconds, thus making accurate simulations feasible also for UWB systems.

The seventh work – *"Band-division vs. Space-division multiplexing: a Network Performance Statistical Assessment"* by A. Ferrari *et al.* – compares the band division multiplexing (BDM) approach against the spatial division multiplexing (SDM) for two selected network topologies. By leveraging the generalized Gaussian noise (GN)-model for quality-of-transmission estimation (QoT-E) and the statistical network assessment for networking analyses, the authors estimate the networking performance as blocking probability versus the total allocated traffic, assuming ITU-G.652D optical fiber for all links. The results show that given the current state of the art, the SDM solution is always the preferable one in case dark fibers are available, while a mixed approach (multi-band and SDM) is the most appropriate in case of limited amount of dark fibers, with a limited penalty with respect to pure SDM, given the multiplexing cardinality.

III. Conclusion and Outlook

This special issue is the result of the strong interest of the scientific community for wideband optical systems as also highlighted by the series of invited papers from network operators and system vendors. This interest is also emphasized by the increasing number of publications and workshops at the main conferences on topics related to wideband, here meant as transmission beyond C-band. This approach is now seen as a valid option to deliver the capacity requested by upcoming applications.

Wideband transmission is not the only possible solution to cope with the almost never-ending traffic growth. In fact, spatial division multiplexing – either in the form of multi-fibers or multi-core / -mode fibers – will also help in addressing these needs. All these solutions will be needed and in different ways for different scenarios. As soon as the upcoming innovation from 5G and machine-to-machine will take off, it will be clearer what it is needed, when and where. As the growth will be most likely heterogeneous, the multi-band approach might have the chance to play an important role in realizing next generation optical systems to support the IT- based society.

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[3] V. Curri *et al.*, "Elastic all-optical networks: A new paradigm enabled by the physical layer. How to optimize network performances?" *J. Lightw. Technol.*, vol. 35, no. 6, pp. 1211–1221, Mar. 2017.

Antonio Napoli received the master's and Ph.D. degrees in electronics engineering from Politecnico di Torino, Turin, Italy, in 2002 and 2006, respectively. He carried out his master thesis with TUWien, Vienna, Austria, in 2002, as part of the ERASMUS program. During his Ph.D., he was a Visiting Researcher with the Polytechnic University of Catalonia, Barcelona, in 2004, and UCL, London, in 2005. In 2006, he joined Siemens COM, which became later, a part of NSN, where he worked on optical transmission up to 400 Gb/s. In 2013, he joined Coriant, where he led the data plane task within the EU FP7 IDEALIST project and coordinated several research activities. Since October 2018, he has been with Infinera Corporation, and continues to work on advanced research. He regularly supervises students and serves as a reviewer for all main IEEE and OSA magazines in his field of interest. He represents Infinera within the PLL Optical WG at OIF and is a (co)-author of seven patents, 44 journals, 103 conferences articles, four OIF contributions, and a book chapter. His research interest includes DSP for high-speed transponders from metro to ultra-long-haul networks, advanced modulation techniques, and wideband optical system design and modeling. In 2016, he was nominated as a Top Reviewer by the IEEE / OSA JOURNAL OF LIGHTWAVE TECHNOLOGY (JLT). He has been twice the Guest Editor for the IEEE / OSA Journal of Optical Communications and Networking and once for IEEE / OSA JLT. He is a Project Reviewer for U.K. governmental organization EPSRC. He served as OFC member (S5, 2018–2020), where he co-organized three workshops (OFC 2017, 2018, and 2020). He is co-organizing an OSA Incubator at OSA HQ in April 2020. Starting from January 2019, he co-coordinates the ETN WON and the EID REAL-NET. He is also involved within the European Flagship Project CiViQ on Quantum Communications.

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Vittorio Curri received the Laurea degree (*cum laude*) in electrical engineer and the Ph.D. degree in optical communications from Politecnico di Torino (PoliTO), Turin, Italy, in 1995 and 1999, respectively. He is a founding member of the OptCom research group and of the PhotonLab, PoliTO. Since 2004, he has been a faculty member with the Department of Electronics and Telecommunications (DET), PoliTo, and is currently an Associate Professor. He is also a Visiting Researcher with the Stanford University, Stanford, CA, USA, and with the UC at Santa Barbara, Santa Barbara, CA. He has been a member of the team first observing then modeling as additive Gaussian noise, the effects of nonlinear propagation on optical coherent technologies, during 2008–2013. In 2014, he started to investigate on the abstraction of data transport for open network planning and management founding the physical layer aware networking (PLANET) research team at PoliTo. He is active as a PI in several institutional- and company-funded research projects investigating on multi-band and multi-service open optical networks. His major research interests are in fiber transmission modeling and simulation, including nonlinearities, transmitter and receiver optimization, design strategies for optical line systems, including PONs, and Raman amplification. He is the PoliTo representative within the consortium Telecom Infraproject, where he is the Scientific Chair of the open-source project for the optical physical-layer softwarization named GNPy. Since 1998, he has also been active in developing software tools for simulation of optical transmission and components. He is a member of the OSA, and has co-authored more than 260 technical papers, including several invited contributions and two JLT Best Paper awards, with a citation count exceeding 5600.