Latest advances in optical networks for 5G communications and beyond

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***Abstract*—This Special Issue contains a collection of outstanding papers covering several recent advances in optical networks for 5G communication 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.**

I. On the Special Issue

This Special Issue (SI) features 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 longer-term research horizon, pointing towards beyond 5G (or 6G) communications, new challenging technical directions are arising that 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 appropriate to announce an IEEE Journal on Selected Areas on 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.

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II. Summary of the accepted articles

The seventeen accepted papers have been classified into four categories: (i) network resource planning; (ii) optical access networks; (iii) optical fronthaul solutions; and (vi) autonomous and data-driven network management.

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 paper "Probabilistic Shared Risk Link Groups Modeling Correlated Resource Failures Caused by Disasters" [1], 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 paper "Resource Allocation in Space Division Multiplexed Elastic Optical Networks Secured with Quantum Key Distribution" [2], 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 paper "Hybrid Trusted/Untrusted Relay Based Quantum Key Distribution over Optical Backbone Networks" [3] 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" [4], where crosstalk considerations are leveraged during defragmentation. Finally, papers "Disruption Minimized Bandwidth Scaling in EON-enabled Transport Network Slices" [5] and "Highly-Efficient Switch

Migration for Controller Load Balancing in Elastic Optical Inter-Datacenter Networks" [6] focus on emerging network management problems in the context of slicing and controller migration in elastic optical networks.

Optical Access Networks

The access segment will have a dominant contribution in the energy consumption of future networks. Papers "Energy-and Bandwidth-Efficient, QoS-Aware Edge Caching in Fog-Enhanced Radio Access Networks" [7] and "SDN-enabled resource management for converged Fi-Wi 5G Fronthaul" [8] 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, papers "Wavelength Division Multiplexed Radio over Fiber links for 5G Fronthaul Networks" [9] and "Experimental Demonstration of Extended 5G Digital Fronthaul over a Partially-Disaggregated WDM/SDM Network" [10] explore novel system architectures for optical fronthaul based on wavelength division multiplexing (WDM) and joint SDM-WDM, respectively.

Optical Fronthaul Solutions

Novel transmission technologies are being investigated to provide, as already mentioned, low-cost and scalable fronthaul solutions. In paper "Reconfigurable Fiber Wireless IFoF Fronthaul with 60 GHz Phased Array Antenna and Silicon Photonic ROADM for 5G mmWave C-RANs" [11], authors experimentally demonstrate a bandwidth-reconfigurable mmWave Fiber Wireless (FiWi) fronthaul bus topology for 5G Centralized-Radio Access Networks (C-RAN), providing a path towards flexible and reconfigurable 5G C-RANs. In paper "Analogue Coherent-Optical Mobile Fronthaul with Integrated Photonic Beamforming" [12], authors experimentally demonstrate a mobile fronhaul methodology using analogue coherent optical transmission of native radio signals. The tunability of electro-absorption modulated lasers used as analogue coherent optical homodyne detectors, is shown to support true-time delay functionality for beam steering phased-array antennas. In paper "Quad-Mode VCSEL Optical Carrier for Long-Reach Ka-Band Millimeter-Wave Over Fiber Link" [13], authors demonstrate the establishment of a long-reach mmWave 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.

Autonomous and Data-Driven Network Management

Network automation based on novel data-driven machine-learning solution is penetrating all network segments, and management in optical networks in particular is now subject of intense innovation. Paper "Latency-sensitive Edge/Cloud Serverless Dynamic Deployment over Telemetry-based Packet-Optical Network" [14] investigates automated deployment and reconfiguration of serverless functions in edge/cloud systems, offering an experimental demonstration of these functions. In paper "Autonomous and Energy Efficient Lightpath Operation based on Digital Subcarrier Multiplexing" [15], authors offer several new guidelines on how to achieve autonomous operation of Digital Subcarrier Multiplexing (DSCM) systems for optical transmission. The paper "A Multi-Task-Learning-based Transfer Deep Reinforcement Learning Design for Autonomic Optical Networks" [16] 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, paper "Invoking Deep Learning for Joint Estimation of Indoor LiFi User Position and Orientation" [17] proposes to use artificial neural networks (ANNs) to jointly estimate the user 3D position and user equipment orientation in indoor LiFi systems.

III. Conclusion and Future Direction

Optical networks are massively-deployed and critical communication infrastructures. They form the physical backbone of today's Internet and they are penetrating always more new domains as access and datacom. To cope with an incessant traffic increase and to comply with new emerging requirements in terms of, e.g., 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. Low-margin design aims at removing traditional design margin (that can be of several dB's), by leveraging more advanced transmission techniques (as probabilistic constellation shaping), and by deriving more accurate device characterizations, typically through monitored data (e.g., elaborated using machine learning). Instead, multi-band networks exploit unconventional fiber bands (e.g., E-, S-, 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 400ZR and 800ZR, 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 128GBd, 140GBd, and 200GBd 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, 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 is related to the (partial) disaggregation and softwarization of optical networks, such as the decoupling of the terminal devices (e.g., 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, 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 modelling, as well as more standard and inter-operable 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", that 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 WiFi and WiFi 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, that, 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 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.

IV. Acknowledgement

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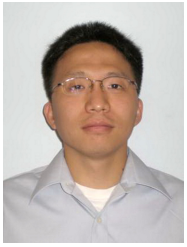

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