Scaling Optical Fiber Capacities

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Optical communication systems form the backbone of today's communication and information society. Approximately six billion kilometers of optical fiber are installed around the globe today, enough to wrap a string of glass as thin as a human hair around the globe about 150 000 times, or 20 times from Earth to Sun and back. Over just a single such strand of optical fiber, cutting-edge optical communication systems are able to carry tens of terabits per second over trans-Pacific distances, taking a mere 50 ms to link North America with South-East Asia. Today's globally installed base of optical communication transponders is collectively capable to transmit several ten exabits per second of information (1 Ebit = 10^{18} bits), sending signals over short links between tens of meters and a kilometer within a data center, over tens of kilometers in links connecting datacenters, in cellular wireless fronthaul and backhaul, and in fiber-to-the-home applications, over hundreds of kilometers in metropolitan and regional networks, and over thousands of kilometers in trans-continental and submarine backbones. In short, almost every bit of information we touch or consume today, whether it belongs to an Internet search, to a streamed video, or to a mobile phone call, lives some parts of its life as an infrared photon within a gigantic global fiber-optic communications infrastructure.

With joint contributions from academia and industry, this special issue provides a balanced overview of the area of fiber-optic network capacity scaling.

Notwithstanding the enormous capacities carried by the various types of fiber-optic networks, the ability to further scale per-fiber capacities is severely lagging the traffic demand, which has led to a "capacity crunch" in optical fiber systems [1], felt in all application areas from short-reach to ultra-long-haul. The problem of the capacity crunch has been in the spotlight of all major optical-communications-related conferences over the past decade, and has been addressed in numerous workshops and symposia, with the active participation of a large community of scientific and industrial researchers and engineers. International standardization organizations have also been looking for new technologies to overcome the capacity crunch. Notably, the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) SG15 has just agreed to issue a technical report on "Optical fiber, cable, and components for space division multiplexing transmission." This Special Issue sheds a light on the problems related to the scalability of fiber-optic networks and various solution paths that are currently being discussed within the fiber-optics community.

Fiber-optic technologies draw from a variety of backgrounds, including classical and quantum photonics, optical, electronic, and integrated optoelectronic device physics and engineering, communications engineering and information processing including information-theoretic approaches, and networking and network engineering. As such, scaling the fiber-optic infrastructure is an inherently multidimensional, multifaceted, and highly interdisciplinary topic area, as is also reflected in this

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issue. The field of optical fiber communications comprises a large and vibrant international scientific and industrial research community. For example, the two largest conferences in the field [Optical Fiber Communication Conference (OFC) and European Conference on Optical Communications (ECOC)] draw thousands of attendees to their technical sessions and more than 10 000 to their associated trade shows. Many very healthy and up-trending scientific journals are covering fiber-optic communications research, most notably the IEEE/Optica JOURNAL OF LIGHTWAVE TECHNOLOGY, the IEEE PHOTONICS TECHNOLOGY LETTERS, the IEEE PHOTONICS JOURNAL, and *Optics Express* (Optica), to name a few. The evolution of the state of the art in fiber-optic technologies is nicely captured in the edited book series *Optical Fiber Telecommunications*, which has appeared in a total of seven editions since its first edition published in 1979 [2], [3], [4], [5], [6], [7], [8]. The current state of technology and research is captured, e.g., in the edited *Springer Handbook of Optical Networks* [9] and in a broad-based Roadmaps review paper [10]. The interested reader may find all of the above pointers helpful in reading up on the field, from its cutting-edge research topics to its commercial implementations and their evolution over the years.

This special issue of the PROCEEDINGS OF THE IEEE provides a snapshot in the area of fiber-optic network capacity scaling. In order to provide the most balanced views possible, each article is written by a team of experts across different institutions as well as across academia and industry.

The Role of Parallelism in the Evolution of Optical Fiber Communication Systems

by W. Klaus et al.

This article serves as an introductory article, highlighting the state of the art in fiber-optic transmission systems, pointing to capacity scalability issues, and laying out various capacity scalability options. The authors show that in order to overcome the capacity limitations of current lightwave systems, massively parallel transmission in the spatial domain [space-division multiplexing (SDM)], supported by extended parallelism in the frequency domain [ultra-wideband systems (UWB)] must be used. The article also reviews key aspects of commercially near-term as well as longer term researched parallel transmission systems, and discusses their architectural and hardware tradeoffs.

Challenges in Estimating the Information Capacity of the Fiber-Optic Channel

by M. Shtaif et al.

This article reviews fiber-optic capacity scaling from an information theoretic perspective, including the difficulties imposed by the nonlinear nature of fiber-optic transmission. The article discusses relevant approximations and regimes of operation in which various bounds for capacity can be effectively assessed, and analyses limits to future capacity scaling through spatial-multiplexing with multimode and multicore fibers.

Coherent Optical Transceivers Scaling and Integration Challenges

by T. Kobayashi et al.

This article addresses hardware and digital signal processing aspects of modern coherent optical transponders, which have revolutionized the optical communications industry over the past decade and have let commercial optical communication systems closely approach their fundamental limits.

Scaling Optical Interconnects for Hyperscale Data Center Networks

by C. Xie and B. Zhang

This article focuses on data center networks operated by hyperscale operators. The scale of those networks has by far overtaken that of traditional carriers due to rapid development and widespread application of cloud computing and Internet services, with traffic doubling almost every one to two years. The article reviews optical interconnect technologies for interdata center interconnects (DCIs), highlighting hyperscale data center network architectures and requirements, as well as differences between DCI optical networks and traditional optical carrier networks. Innovations in data plane as well as in control and management plane technologies are being discussed.

Flexible Technologies to Increase Optical Network Capacity

by A. Lord et al.

This article provides a perspective from traditional network operators. The focus of this article is on optimizing wavelength routing around the network, maximizing the benefits arising from fine-control coherent digital signal processing with increasingly accurate real-time monitoring, and the deployment of multiband and multifiber connectivity to cope with exponentially increasing traffic demands to support broadband access and 5G wireless applications.

Ultrawideband Systems and Networks: Beyond $C + L$-Band

by T. Hoshida et al.

This article explores optical fiber transmission systems and networks utilizing extended optical amplification bands beyond the C-band and L-band commercially used today. The article discusses merits and challenges of such ultrawideband optical transport systems and networks.

Devices and Fibers for Ultrawideband Optical Communications

by J. Renaudier et al.

This article extends the system-level aspects of ultrawideband networks to a device level and explores devices and subsystems that are needed to construct such networks, including the design and fabrication of lasers, optical amplifiers, optical switches, and optoelectronic modulators for ultrawideband applications. In addition, the article reviews advances in ultrawideband optical fibers.

Ultrahigh Fiber Count and High-Density Cables, Deployments, and Systems
by T. Sasaki et al.
This article reviews the state of the art in optical fiber cabling and deployment technologies. Modern high-density optical fiber cables can carry thousands of optical fiber strands and hence represent a massively parallel transmission medium, suitable for the massive spatial parallelism that will be needed to scale fiber-optic network capacity.

Weakly Coupled Multicore Fiber Technology, Deployment, and Systems
by T. Matsui et al.
This article explores the integration of high fiber-count optical cables using multicore optical fibers to realize even higher degrees of spatial parallelism in the future than what can be achieved today. The article focuses on weakly coupled multicore fiber technology and reports on commercial progress as well as on ongoing standardization efforts in the ITU-T and the International Electrotechnical Commission (IEC) to accelerate the practical application of SDM technology. The article goes beyond the multicore fiber itself and covers aspects such as splicing, connectors, and input–output technologies.

Randomly-Coupled Multi-Core Fiber Technology
by T. Hayashi et al.
This article considers an even higher-density spatially parallel integration technique that allows for random coupling between the cores of multicore fibers. Compared to weakly coupled multicore fibers, such fibers simultaneously realize higher spatial channel density and ultralow transmission loss using existing ultralow-loss single-mode fiber core designs. In addition, the article shows that the strong mode coupling characteristics of randomly coupled multicore fibers can provide favorable optical properties such as suppressed accumulation of modal dispersion, mode-dependent loss, and nonlinear impairments.

Few-Mode Fiber Technology, Deployments, and Systems
by P. Sillard et al.
This article reviews the third advanced category of SDM fibers, which use the coupled waveguide modes of few-mode fibers in conjunction with multiple-input–multiple-output (MIMO) digital signal processing to achieve the highest spatial information density. The article reviews the most recent advances in design and fabrication of related fibers and systems.

Photonic Lanterns, 3-D Waveguides, Multiplane Light Conversion, and Other Components That Enable Space-Division Multiplexing
by N. K. Fontaine et al.
This article reviews the mode shaping technologies needed to perform mode division multiplexing on few-mode fibers. The article discusses implementations and trade-offs of four different techniques: multiplane light conversion, fused fiber devices, 3-D waveguides in glass, and free-space imaging systems.

Optical Switching in Future Fiber-Optic Networks Utilizing Spectral and Spatial Degrees of Freedom
by D. Marom et al.
This article examines the capacity scaling requirements of optical networks from a switching perspective that leverage both spectral and spatial degrees of freedom. The authors discuss various networking scenarios such as intra/inter datacenter, terrestrial, undersea, and wireless 5G/6G hauling networks and identify the best utilization plan and key attributes that can be harnessed by the offered spectral and spatial degrees of freedom for each scenario.

Using Global Existing Fiber Networks for Environmental Sensing
by E. Ip et al.
This article reviews recent advances in distributed fiber optic sensing and their applications. This allows the vast installed base of telecommunications fibers and transponders to be leveraged as a globally distributed sensor. The article summarizes recent experimental and field trial results where fiber-optic sensing was used in such wide-ranging applications as geohazard monitoring, seismic monitoring, traffic monitoring, and infrastructure health monitoring.

Apart from thoroughly reviewing its field, each article also presents new and original insights. We, therefore, hope that this issue serves the novice and expert alike and gives a good overview in the area of fiber-optic capacity scaling. ■

Happy reading!

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ABOUT THE GUEST EDITORS

Peter J. Winzer (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the Technical University of Vienna, Vienna, Austria, in 1998.

Supported by the European Space Agency, he investigated space-borne Doppler lidar and laser communications. From 2000 to 2019, he was at Bell Labs, Holmdel, NJ, USA, where he focused on fiber-optic communication systems and networks and contributed to many high-speed optical transmission records up to 1 Tb/s per carrier, including the first field trial of live 100G video traffic. Following his involvement in estimating the optical fiber Shannon capacity, he investigated spatial multiplexing (SDM) and multiple-input–multiple-output (MIMO) techniques to scale optical transport systems. Before leaving Bell Labs in 2019, he led its global optical transmissions research efforts. He then founded the venture capital-backed startup Nubis Communications, New Providence, NJ. With over 500 coauthored publications and over 80 granted patents, he has widely published and patented.

Dr. Winzer is actively involved with the IEEE Photonics Society and the Optical Society (OSA, now Optica). He is a highly cited researcher, a Bell Labs Fellow, a Fellow of the OSA, and an elected member of the U.S. National Academy of Engineering (NAE). He received multiple awards, including the John Tyndall Award, and holds an honorary doctorate from the Technical University of Eindhoven. He was the Program Chair of the 2009 European Conference on Optical Communications (ECOC) and the Program/General Chair of the 2015/2017 Optical Fiber Communication Conference (OFC). He served as the Editor-in-Chief for IEEE/OSA Journal of Lightwave Technology from 2013 to 2018.

Kazuhide Nakajima (Member, IEEE) received the M.S. and Dr.Eng. degrees from Nihon University, Chiba, Japan, in 1994 and 2005, respectively.

He has been a Senior Distinguished Researcher with NTT Corporation, Tokyo, Japan, since April 2019. His research interests include optical fiber technologies for communication and other applications. He has engaged in design and characterization of both traditional and holey optical fibers. Recently, he has intensively been discussing about an optical fiber for space division multiplexing transmission. He joined Access Network Systems Laboratories, NTT Corporation, in 1994. He has been acting as a Rapporteur of Question 5, study group 15 of the International Telecommunication Union Telecommunication Standardization Sector (ITU-T).

Dr. Nakajima is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) and the Optical Society (OSA). He served as a Technical Program Committee Member of the Optical Fiber Communication Conference (OFC), the Opto-Electronics and Communications Conference (OECC), the Optical Fiber Sensors (OFS), and so on, and he has organized several workshops in these international conferences. Recognition of his work includes several best paper awards in international conferences and several achievement awards from Japanese Minister/Associations.

Cristian Antonelli (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of L'Aquila, L'Aquila, Italy, in 2006.

He is an Associate Professor at the University of L'Aquila. He is the Founder and the Head of the Laboratory of Optics and Photonics of INCIPICT, University of L'Aquila, which is the first infrastructure worldwide incorporating installed fibers for space-division multiplexed communications (http://incipict.univaq.it). This infrastructure is envisioned to function as an open lab in the service of the optical communications community. His research interests include various aspects of fiber-optic communications, with special emphasis on the modeling of propagation effects and their impact on system performance.

Dr. Antonelli served as a technical program committee member for the major optics and photonics-related international conferences, including the Optical Fiber Communication Conference (OFC), from 2015 to 2018, and from 2020 to 2022, the European Conference on Optical Communications (ECOC) in 2018, from 2020 to 2022, the Opto-Electronics and Communications Conference (OECC) in 2019, and the Conference on Lasers and Electro-Optics (CLEO) from 2011 to 2013, and organized numerous workshops on SDM transmission. He is a Fellow of OPTICA (formerly OSA). He served as an Associate Editor for IEEE/OSA Journal of Lightwave Technology from 2014 to 2019. Since 2020, he has been serving as a Topical Editor for *Optics Letters.*