The Evolution of Optical Networking

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In 2010, the scientific and engineering communities celebrated the 50th anniversary of the first demonstration of the laser, the 40th anniversary of the first demonstration of a low-loss optical fiber, and the Nobel Prize award to Dr. Charles Cao, who first proposed silica as a practical material for long-distance optical fiber communication. These innovations facilitated the optical telecommunications revolution that started in the mid-1970s and continues today. From the first point-to-point fiber optic connections at megabit per second rates over several kilometers to today's multiterabit ultralong-haul dense wavelength-division multiplexed systems, optical communication networks have experienced remarkable year over year increases in productivity, as measured by capacity growth, cost reduction, and increased automation and flexibility. In addition to the aforementioned milestones, we decided to organize a special issue on the "Evolution of Optical Networking" to celebrate the centennial anniversary of the PROCEEDINGS OF THE IEEE marking the aforementioned occasions but also the impact and enhanced quality of life that optical networking has brought to our society.

The topics of this special issue cover the evolution of the optical networking solutions that have shown the greatest impact over the past years and the largest potential for the future, and include topics from optical network technologies to optical network architecture, algorithms and protocols, from core to access network segments.

Today, the term "optical networks" denotes high-capacity telecommunications networks based on optical technologies and components that can provide capacity, provisioning, routing, grooming, or restoration at the wavelength level. It is well understood and appreciated that optical networking through the increased capacity it offers at a reduced cost per transmitted bit per kilometer compared to other long-distance

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networking technologies (like wireless networking, copper/coaxial cable/powerlines-based wireline networking) has enabled the internet revolution that started in mid-1990s and has resulted in tremendous impact to our society. Optical networking solutions span the full spectrum of transport networks from core backbone and metro down to the access network domains. Backbone and metro networks carry highly aggregated high bitrate data traffic covering distances that span from a city size up to a whole continent. The access network carries different kinds of data streams to and from private and business customers, which are multiplexed/demultiplexed in nodes having fixed back-hauling connections to the transport core network. The use of optical networking is certainly dominating the core and metro network segments and more recently has started its expansion to the access network segment as well.

The first optical networks operated on a single wavelength per fiber and were opaque, i.e., the signal on a path was regenerated through opto-electronic conversions at each traversed node, and all signal switching and processing functions were implemented in the electronic layer. This first generation of optical networking encompasses the adoption of the synchronous optical network (SONET/SDH), a framework that standardized line rates, coding schemes, bitrate hierarchies, and operations and maintenance functionality, as well as the types of network elements required, network architectures that vendors could implement, and the functionality that each node must carry out.

Since the mid-1990s, a new technique was introduced to optical communication networks supporting transmission of tens of optical signals over a single optical fiber. This technique is called wavelength division multiplexing (WDM) and, besides offering large transmission capacities per optical fiber, has enabled the realization of wavelength routed networks with the use of either electronic or all-optical-based switching nodes. Multiwavelength optically routed networks constitute the second generation of optical networking.

State-of-the-art backbone core and metro optical networks rely heavily on high-capacity optical transmission links utilizing WDM. Traditional network planning solutions in optical networking are based on the use of predetermined fixed capacity connections among network nodes comprising permanent and preplanned add/drop wavelengths channels. In such networks, the bitrate for each wavelength must be chosen among a small set of available bitrates per wavelength, namely 10 , 40, and most recently, 100 Gb/s. The network design optimization is then a complex process that is most often carried out in two steps.

The traffic matrix of individual connection demands is first groomed into aggregated demands fitting the capacity granularity available in the optical layer. The aim of this step is to minimize the number of required wavelengths in the optical layer, which generally translates into lower wavelength contention issues, lower number of required resources, and hence lower costs. This also fixes the number of 10- and 40-Gb/s wavelengths to be used in the network. The second step of the network optimization is then carried out through routing and wavelength assignment (RWA) algorithms which assign a path and a wavelength to each aggregated demand taking into account the topology of the network and physical impairments. The most common criterion for optimization is the minimization of the network cost that often correlates with minimizing the number of required optoelectronic regenerators (that are required to clean up the signals for distortions and noise, allowing transmission over thousands of kilometers) for the overall network. The wavelength needs to be chosen among a set fixed by the International Telecommunications Union (ITU) frequency grid (i.e., with 50- or 100-GHz spacing). Flexibility in these networks is limited to that allowed by the tunable lasers (i.e., each transponder is not assigned to a fixed wavelength) and limited reconfigurations are allowed by optical switching nodes.

However, the network does not stay indefinitely in the configuration defined during the network planning phase. Network configurations may change during the planning phase due to either traffic change (usually an increase) or link/node failures. The introduction of reconfigurable optical add/drop multiplexing (ROADM) and wavelength selective switching (WSS) technologies today provides an additional degree of freedom to the implementation of network engineering, allowing the reconfiguration of connections when traffic demands increase or are modified.

The current approach to dynamicity in deployed optical networks leaves established connections untouched (until obsolete or faulty) and handles new connection requests or failure by using overprovisioned free resources (or by suggesting where additional resource like transponders should be placed). This causes minimal disruption to the already established traffic, but it is easily shown that it yields network configurations departing significantly from the optimal resource allocation. Incremental increases of the capacity in a network (every few years) are typically handled in this manner. However, a significant drawback still remains unresolved and this is related to the stranded (underutilized) bandwidth issue due to the coarse and rigid granularity of the system (that is, the granularity at the wavelength level), which is obvious especially when only a small portion of the fully allocated wavelength channel capacity is used.

The control and management planes of optical networks are responsible for the distributed management and coordination of the different elements composing the network, introducing automatic and intelligent functions in order to provide fast and automated end-to-end connection provisioning and traffic engineering (TE) with protection and restoration. The control plane in particular is the corner stone for the success of next-generation intelligent optical networks and many standardization organizations such as the Internet Engineering Task Force (IETF), the Optical Internetworking Forum (OIF), and ITU have been intensely working on the relevant issues. The main responsibilities of the control plane include routing information dissemination, path computation, signaling, connection establishment, and resource management, implemented in terms of control protocols executed between communicating entities.

It is widely acknowledged that generalized multiple protocol label switching (GMPLS) is the best candidate for the optical control plane, especially suitable for the envisioned paradigm of IP-over-WDM. While there is a basic set of features supported by the recommendations for GMPLS protocols implementation, there are some drawbacks mainly due to the immaturity of this technology. Great efforts are being spent on the development of new features enhancing the GMPLS control plane performance. An integrated GMPLS-based multilayer and multidomain control plane, which allows a more efficient use of the network resources, is a key objective for the upcoming years.

Core/metro optical networks that have been deployed over the past few years demonstrate excellent performance with respect to the requirements of the present day needs and have improved considerably over the past generation deployed networks. However, currently deployed optical networks work with equipment/devices developed for very rigid specifications: fixed grid spacing, fixed modulation format, fixed bitrates. This makes the process of upgrading the network very cumbersome as either a large number of components need to be changed (with the associated high capital expenditure required) or changes are limited by the narrow range of adaptability of existing components. Network agility and resource allocation elasticity that would be enabled by new network elements (e.g., tunable wavelength transponders, colorless, directionless, contentionless, and grid-less wavelength selective switches, bitrate flexible interfaces) will be certainly needed for the future networks and will enable a new generation of high-performance/quality applications/services offered to the end users with a lower cost.

In the access network domain, over the next few years, the copper and coaxial links that currently constitute the majority of installed infrastructure will be replaced by optical fibers and the fiber-based network will move closer and closer to end users. Customers can and will require new communication services with a high availability and short time intervals for data download and upload. Present fiber-to-the-home (FTTH) optical access systems mainly use point-to-point (PtP) and passive optical network (PON) architectures/technologies with a trend to extend reach and number of users connected per access node, which enables reduction of central offices in the access area. Such strategies may assist in introducing fiber optical infrastructure in the access domain. Exploitation of use of WDM technology in optical access networks is under R&D, but it is expected that soon it will be ready for prime time.

Optical fiber networks provide a high-capacity infrastructure for serving the growing traffic demand. In that respect, optical networks have an increasing significant impact to our society and our quality of life. Governments, research agencies, universities, and the telecommunications industry are investing heavily in optical networking related research with the goal to derive innovations that significantly will improve the capacity of the future networks while at the same time increasing the cost and energy efficiency of the overall solutions to be deployed. In light of these facts, this special issue presents the latest developments in optical network research and the latest advancements in the deployment of such technologies. It also addresses the challenges for realizing converged optical network infrastructures in order to support the future internet and grid service deployments in a sustainable, reliable, integrated, and scalable way.

The topics of the special issue have been selected by the guest editors in an effort to cover the evolution of the optical networking solutions that have shown the greatest impact over the past years and the largest potential for the future. The topics span many areas from optical network technologies to optical network architecture, algorithms and protocols, from core to access network segments and from the past to the future of optical networking. A set of well-recognized scientists from both industry and academia were invited to contribute to this special issue as lead authors. They were chosen based on the fact that they are experts on the topics of the respective papers and have made pioneering contributions to the development of optical networking research.

A brief description of the contents of this special issue is as follows.

The first paper is entitled "The evolution of configurable wavelength multiplexed optical networks—A historical perspective." It presents the early history developments in the field of optical networking, while it also summarizes the role, vision, challenges, successes, value, and unfinished business of optical networking.

The paper on "Capacity trends and limits of optical communication networks" presents a discussion of network traffic evolution trends, the capacity required to support the traffic, and the practical challenges faced to realize the required capacity. Among the latter are basic limits to communication channel capacity raised by the laws of physics and information theory.

The paper "Wavelength-selective reconfiguration in transparent agile optical networks" traces the history of reconfigurable WDM networks and highlights the key function of reconfigurability on wavelength-selective basis. The paper highlights some emerging requirements of wavelength-selective switches, including the need to deal with flexible channel spectrum assignments and colorless, directionless, and contentionless (CDC) switching. The authors conclude with a perspective on future research directions.

In "100-G and beyond transmission technologies for evolving optical networks and relevant physical-layer issues," the authors outline the technologies that are enabling the next-generation optical fiber communication systems, where each wavelength channel can support 100-Gb/s and higher rates.

In the paper "Optical flow switching networks," the concept of flow switching is demonstrated to be an option for rate growth compliance while being power efficient and cost effective. Its features are presented and discussed in detail.

The paper entitled "Optical network management and control" discusses from the point of view of a large telecommunication carrier perspective how optical networks are managed, controlled, and operated.

The vision of an all-optical network, one in which signals remain in the optical domain from source to destination, has inspired the imagination of researchers for a number of decades. The paper "All-optical networking—Evolution, benefits, challenges, and future vision" provides a comprehensive overview of the evolution of all-optical networking.

The authors of the paper "Cross-layer approaches for planning and operating impairment-aware optical networks" present some recent developments on a research topic that attracted attention over the past few years. The authors provide an overview of the associated challenges, report comparative analysis with a selection of existing solutions, and present an overview of the open issues for future research.

In the paper "Next-generation optical network architecture and multidomain issues," the authors discuss the fact that automated operation of optical networks has reduced operations costs and enabled customer control of high bandwidth services. In the future, they foresee that application-driven control of optical networks will become a reality and they describe the emerging technologies, both at the physical layer and network control layer, with a goal of assessing their impact on next-generation optical network architectures.

The paper "Multilayer and multidomain resilience in optical networks" focuses on the issue of how to handle failures in an optical network. A failure of an optical network element, e.g., due to a fiber cut or a node failure, can lead to a large loss of capacity. The author of this paper reviews optical network resilience in two dimensions: 1) multilayer resilience, which takes advantage of recovery options on different technology layers, e.g., optical layer as well an Internet protocol (IP) layer; and 2) multidomain resilience, which ensures end-to-end services to reach survivability levels across multiple network domains, each of which could be operated by a separate entity, and the internal details of a domain may not be visible to the other domains.

The authors of the paper "Optical networks for grid and cloud computing applications" discuss the role of optical networks in supporting emerging applications through the development of grid and cloud computing paradigms. The authors outline the novel requirements of these applications, including performance attributes as well as ability to adapt to changing demands and potential failures. The solutions include interworking of optical transport, any-cast routing, virtualization, and appropriate control plane extensions. The paper identifies challenges and research opportunities that can enable future-proof optical cloud systems, such as enabling the virtualization concept in optical networks.

In the paper "Energy challenges in current and future optical transmission networks," the authors highlight the fact that, like all areas of contemporary human endeavor, it is incumbent upon communication networks to function in an efficient, affordable, sustainable, and ecologically mindful manner. Beneficially, it is considered that the information and communication technology (ICT) sector can also be leveraged to substantially reduce the energy consumption in other sectors. All these issues and trends are highlighted in this paper.

In "Evolution of optical access networks: Architectures and capacity upgrades," the authors present an overview of PON technologies and discuss the PON's role in the evolution of optical access networks from an architectural perspective. To accommodate a growing base of PON users and their higher bandwidth needs, methods to upgrade a PON's capacity seamlessly are outlined, and various PON evolution strategies are discussed for efficient, gradual, demand-based migration.

Finally, the paper "Hybrid optical–wireless access networks" discusses how the next-generation access networks are expected to provide mobility, large data bandwidth, high quality of service (QoS), and ubiquitous coverage. The authors review relevant research efforts in this field and highlight remaining challenges and research topics to motivate further investigations into optical–wireless access networks.

As guest editors, it is our pleasure to present this collection of papers on the Evolution of Optical Networking to the readership of the Proceedings of the IEEE. In closing, we would like to acknowledge the authors and reviewers for their invaluable contributions and time. We are also grateful to the staff of this Journal's editorial board, especially to the managing editor Jim Calder and the publications editor Jo Sun. ■

ABOUT THE GUEST EDITORS

Ioannis Tomkos received the B.Sc. degree in Physics from University of Patras, Greece in 1994, the M.Sc. in telecommunications engineering and the Ph.D. degree in optical telecommunications from University of Athens, Athens, Greece in 1996 and 1999, respectively.

He has been with the Athens Information Technology Center (AIT), Athens, Greece, since September 2002. In the past, he was Adjunct Faculty member at the Information Networking Institute, Carnegie Mellon University, Pittsburgh, PA (2002–2010), Senior Scientist at Corning Inc., Corning, NY (1999–2002), and Research Fellow at University of Athens, Athens, Greece (1995–1999). Dr. Tomkos is representing AIT as Principal Investigator in many European Union funded research projects (including five active) and has a consortium-wide initiator/leader role. Together with his colleagues and students he has authored about 420 peer-reviewed archival articles, including over 110 journal/magazine/book publications and 310 conference/workshop proceedings papers.

Dr. Tomkos was elected in 2007 as Distinguished Lecturer of the IEEE Communications Society for the topic of transparent optical networking. He has served as the Chair of the International Optical Networking Technical Committee of the IEEE Communications Society (2007–2008) and the Chairman of the IFIP working group on "Photonic Networking" (2008–2009). He is currently the Chairman of the OSA Technical Group on Optical Communications (2009–2012) and the Chairman of the IEEE Photonics Society Greek Chapter (2010–2012). He is also Chairman of the working group "Next Generation Networks" of the "Digital Greece 2020" Forum. He has been General Chair, Technical Program Chair, Subcommittee Chair, Symposium Chair, or/and member of the steering/organizing committees for the major conferences in the area of telecommunications/networking (more than 100 conferences/workshops). In addition, he is a member of the Editorial Boards of the IEEE/OSA Journal of Lightwave Technology, the IEEE/OSA Journal of Optical Communications and Networking, the IET Journal on Optoelectronics, and the *International Journal on Telecommunications Management*. He is a Fellow of the Institute of Engineering and Technology (IET).

Steven K. Korotky (Fellow, IEEE) received the A.B. degree and graduated Phi Beta Kappa with high honors in physics from Rutgers College of Rutgers University, New Brunswick, NJ, in 1975 and received the M.S. and Ph.D. degrees in physics from Yale University, New Haven, CT, in 1976 and 1980, respectively.

He is Distinguished Member of Technical Staff, Optical Networking Research, at Bell Laboratories, Alcatel-Lucent, Holmdel, NJ. He joined Bell Labs in 1980, and in addition to Research Principal Investigator, has held the positions of Technical Manager, Senior Manager, and Director, Optical Networking Applications and Technology, for the CTO office of Lucent's Optical Networking Business Group. The focus of his research and development activities has been in the areas of integrated optics, photonic circuits, and lightwave communications with emphasis on: optical waveguides, high-speed optical modulation and pulse generation, optical switching and cross connects, metro and long-distance photonic transmission systems and networks, and most recently the evolving trends and requirements of backbone fiber mesh networks. He holds 23 patents and has coauthored over 180 journal and conference publications and five books on the subject of integrated optics and optical fiber communication.

Dr. Korotky is a member of the American Physical Society (APS) and a Fellow of the Optical Society of America (OSA). He has served on the technical program committees of several IEEE and OSA meetings and conferences and on the IEEE Lasers and Electro-Optics Society (LEOS) Board of Governors. He has served two terms as Topical Editor of Applied Optics and two terms as Associate Editor of the *Journal of Optical Communications and Networking*. Currently, he is serving a second term as Associate Editor of the *Bell Labs Technical Journal*. He received the Bell Laboratories Distinguished Member of Technical Staff Award in 1990 and was a member of the teams receiving the Bell Labs President's Gold Award in 2000 and 2004.

Biswanath Mukherjee (Fellow, IEEE) received the B.Tech. degree from the Indian Institute of Technology (IIT), Kharagpur, India, in 1980 and the Ph.D. degree from the University of Washington, Seattle, in 1987.

He is Distinguished Professor at University of California—Davis, Davis, where he was Chairman of Computer Science during 1997–2000. He has supervised 47 Ph.D. students to completion and currently has 20 advisees, mainly Ph.D. students. He is author of *Optical WDM Networks* (New York: Springer-Verlag, January 2006). He served a five-year term on Board of Directors of IPLocks, a Silicon Valley company. He has served on Technical Advisory Board of several startup companies.

Dr. Mukherjee was Technical Program Committee (TPC) Co-Chair of the 2009 Conference on Optical Fiber Communication (OFC) and TPC Chair of the 1996 IEEE Conference of the IEEE Computer Societies (INFOCOM). He is General Co-Chair of the 2011 OFC Conference. He is Editor of Springer's Optical Networks Book Series. He has served on eight journal editorial boards, most notably the IEEE/ACM Transactions on Networking and IEEE Network. He is co-winner of Optical Networking Symposium Best Paper Awards at IEEE Globecom 2007 and 2008.

Rodney S. Tucker (Fellow, IEEE) received the B.E. (Elec.) and Ph.D. degrees from the University of Melbourne, Melbourne, Vic. Australia, in 1969 and 1975, respectively.

He is a Laureate Professor at the University of Melbourne. He has previously held positions at the University of Queensland, the University of California, Berkeley, Cornell University, Plessey Research, AT&T Bell Laboratories, Hewlett Packard Laboratories, and Agilent Technologies. He joined the University of Melbourne in 1990. He is Director of the University of Melbourne's Institute for a Broadband-Enabled Society (IBES) and the Centre for Ultra-Broadband Information Networks (CUBIN). He is Australia's preeminent research leader in telecommunications, optical fiber technologies, and fiber-to-the-home access networks. He has a high profile in Australia and internationally, and is renowned for his extensive experience in the research, development, and application of advanced technologies for broadband access, including passive optical networks and fiber–wireless systems. He currently leads R&D teams working on technologies and deployment strategies for extended-reach passive optical networks for rural and remote areas, and on energy and environmental issues associated with broadband access.

Dr. Tucker is a Fellow of the Australian Academy of Science, a Fellow of the Australian Academy of Technological Sciences and Engineering, and a Fellow of the Optical Society of America. He is a regular keynote speaker at international conferences on optical communications. He served as a member of the Federal Government's Panel of Experts tasked with evaluating proposals for the National Broadband Network. He served on the Management Committee of the Australian Telecommunications and Electronics Research Board from 1991 to 1993, and has been a member of the Australasian Council on Quantum Electronics. From 1995 to 1999, he served as a member of the Board of Governors of the IEEE Lasers and Electro-Optics Society. He was Editor-in-Chief of the IEEE Transactions on Microwave Theory and Techniques from 1988 to 1990 and Associate Editor of IEEE Photonics Technology Letters from 1997 to 2006. He is currently Vice-President, Publications of the IEEE Photonics Society. In 1975, he was awarded a Harkness Fellowship by the Commonwealth Fund, New York. He received the Institution of Engineers, Australia, M.A. Sargent Medal for 1995 for his contributions to Electrical Engineering and was named IEEE Lasers and Electro-Optics Society Distinguished Lecturer for the year 1995–1996. In 1997, he was awarded the Australia Prize (later renamed the Prime Minister's Prize for Science), Australia's premier award for science and technology, for his contributions to telecommunications. In 2007, he was awarded the IEEE Lasers and Electro-optics Society Aron Kressel Award for his pioneering contributions to high-speed semiconductor lasers. He is one of the 200 most published authors in the field of engineering and has been named one of ISI's Highly-Cited Researchers.

Leda Lunardi (Fellow, IEEE) received the B.S. and M.S. degrees in physics from University of São Paulo, São Paulo, Brazil and the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY.

She has been a Professor at the Electrical and Computer Engineering Department, North Carolina State University, Raleigh, since 2003. She has spent her career in industry before joining academia. Her recent research includes optoelectronics and amorphous transistors integration. From 2005 to 2007, as a rotator, she was Program Director for the Electrical, Communications and Cyber Systems (ECCS) Division in the Engineering Directorate of the National Science Foundation (NSF), Arlington, VA.

Prof. Lunardi has served on several IEEE executive and technical committee conferences, national and international governments' ad hoc committees for grants and projects reviews. Some of her present technical volunteer activities include the editorial board for the Proceedings of the IEEE, editor for the IEEE Transactions of Electron Devices (Optoelectronics Devices), and treasurer for the IEEE Photonics Society Eastern Carolina Chapter. She shared the 2000 IEEE Photonics Society Engineering Achievement Award for her contributions on monolithically integrated photoreceivers for optical communications.