Guest Editorial
WDM-Based Network Architectures

RECENT developments in wavelength division multiplexing (WDM) technology have led to a tremendous amount of commercial and research interest in WDM-based networks. Until recently, WDM has been used primarily for point-to-point long haul transmission. However, with the emergence of WDM networking components, people are beginning to design and deploy WDM-based networks that take advantage of the flexibility and configurability of these components. For the first time since the emergence of this field, research in this area has found commercial applications. The goal of this issue is to address WDM networking research that can have an impact on the way WDM networks will be designed and deployed over the next several years. In particular, this issue is focused on papers dealing with the design of multihop WDM networks for access, metropolitan, or wide area applications.

It is interesting to observe the progress in this field by examining the topics covered by earlier special issues on optical networks. In fact, the progress has been immense! Looking back at the August 1990 IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS/IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY special issue on WDM networks, we note that at that time, papers were primarily focused on WDM technologies. Some of the papers in that issue described early experimental testbeds, many dealt with system issues (e.g., cross-talk analysis, nonlinearity issues, etc.), but the majority of the papers described WDM components such as multiplexers, lasers, detectors, etc. A few years later, the June 1996 special issue on optical networks started to address higher layer network issues. A few papers in that issue described on-going experimental testbeds, and most papers dealt with network layer design issues such as routing and wavelength assignment, benefits of wavelength conversion, and logical topology design. Clearly, progress was made from subsystems to networks, yet mostly at the experimental stage. Obviously, this earlier work paved the way toward the present day boom of optical networks in the commercial marketplace.

As optical networks begin to emerge commercially, deployment issues are of critical importance, and largely this is the focus of this issue. In this issue we feature articles that cover topics related to optical network management such as network survivability and fault management as well as network reconfiguration. Also included are papers on topology design issues, such as traffic grooming, logical topology design, and network dimensioning. Finally, included are a few papers on the topic of optical packet switching. Clearly, this last topic is not of present day commercial viability, but it represents a future direction in optical networking.

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The papers in this special issue are organized into six sections.

The first section addresses the general problem of survivable optical networks. The section begins with a paper by Colle *et al.* on the survivability of data centric networks. It presents a thorough overview of existing survivability/resilience mechanisms in IP over WDM networks and suggests new survivability concepts for optical networks. In this paper, different case studies discussing network performance and cost issues are also analyzed and evaluated (e.g., cost evaluation of multiprotocol labeled switching (MPLS) and MPLambdaS protection, impact of MPLS restoration on the TCP flows, and the study of the overall IP over optical transport network (IP-OTN) cost versus OTN and IP recovery schemes). The second paper in this section is authored by Sahasrabuddhe *et al.* and it compares, using sophisticated integer linear programming (ILP) formulations and heuristics, the WDM protection and IP restoration techniques in IP-over-WDM networks. With the current prevalence of the Internet, and increasing development and deployment of intelligent optical network (ION) elements, the author's comparison of the relative merits of restoration for each of the different network levels, and especially the capacity requirements and the recovery times, is very timely and relevant. The third paper in this section by Sridharan *et al.* presents solutions to the problem of online reconfiguration of lightpath requests in the event of link and node failures in WDM networks. The authors use heuristics to reduce the size of the corresponding ILP to yield feasible results. Their ideas for possible rerouting of some of the primary/backup paths to recover additional capacity offer new avenues to explore in the area of network reoptimization. The last paper in this section is written by Grover and Doucette and it presents a new method for mesh restoration in WDM networks by abstracting the original mesh network into a meta-mesh. Restoration in this case is performed by restoring the higher level bypass chains rather than the links themselves. By evaluating their approach in networks with small degree nodes and comparing it with rings, the authors demonstrate the value of mesh restoration even for sparse networks. Their ideas of express flows bypassing the optical add–drop multiplexers (OADMs) and the fact that no spare capacity is reserved in the chain for the restoration of express flows is also very important as it is related to the "glassthrough" ideas that are currently explored by a number of carriers.

The second section of this issue deals with the design of logical topologies and network reconfiguration. The first paper in this section by Arora *et al.* examines how to embed a logical topology onto a WDM network where the WDM network is a line or ring network. The logical topologies studied are those that have minimal diameter. Lower and upper bounds on the diameter are given including topologies that achieve the upper bounds. The second paper in this section, authored by Narula-Tam *et al.*, investigates wavelength requirements for

WDM ring networks and proposes bounds and heuristics for routing in such networks. The paper studies worst case bounds on resource requirements for embedding any arbitrary logical topology on ring topologies. In addition, some heuristics are also presented for reducing the resource requirement on average networks. These results are very useful in WDM networks design. Following the analysis in this paper, for a given ring, network designers can decide how many wavelengths should be used to achieve an optimal assignment for a significant fraction of possible logical topologies.

The third section deals with the issue of multicast in WDM networks. The first paper by Ramesh *et al.* presents an approximate analysis of call-blocking probability for an arbitrary WDM mesh network for multicast calls in addition to multiple classes of calls. This paper demonstrates the applicability of a given model for computing blocking probabilities of single-class calls to multiclass unicast and multicast calls. It shows that blocking of multiclass calls is class-independent and that the blocking probability on an arbitrary route can be obtained by aggregating calls belonging to the different classes into a single class. It also shows how multicast calls can be handled using the same framework. The second paper by Chen and Wang presents an optimal (cost-wise) wavelength assignment for the routing of multicast connections in WDM networks with such constraints as wavelength conversion cost, transmission cost, and wavelength cost. In addition, the paper proposes a simple heuristic to construct a multicast tree based on Dijkstra's algorithm.

The fourth section of the special issue addresses traffic grooming. This topic is one of the most important topics in today's networks where network nodes need to switch traffic demands which can be at different rates (OC-3, OC-48, OC-192, OC-768) in the hierarchy. Services at OC-48 and OC-192 rates arise from the interconnection of IP routers with OC-48 and OC-192 interfaces. Sub-OC-48 services also arise from the interconnection of IP routers/ATM switches with OC-3, and OC-12 interfaces as well as from leased and private-line traffic. Grooming the subwavelength traffic onto wavelengths is one of the areas of great importance for both the carriers that deploy intelligent network elements and the equipment vendors that develop such elements. The first paper in this section by Dutta and Rouskas addresses the interesting and important problem of optimally grooming traffic on a WDM ring to minimize electrooptic conversions. This is an important problem because one of the rationales for all-optical networks is reduced cost due to the minimization of expensive electrooptic conversions (WDM transponders/grooming port cards). Since the problem is NP-hard, the authors try to give lower and upper bounds. Such bounds are interesting because, potentially with little computational effort, we can achieve an upper bound (which also gives a feasible solution) while at the same time obtain a lower bound. The gap between the upper and lower bounds indicates how good the solution is. The second paper, by Zhu and Mukherjee, investigates traffic grooming and routing and wavelength assignment (RWA) in a WDM mesh network. Given a specific set of subwavelength traffic requests, the authors study how to maximize the amount of the traffic that can be accommodated in a given (fixed) physical topology. An ILP formulation of this problem is given and two heuristics are proposed and compared.

The fifth section covers the technical issues associated with network design. The first paper in this section by Nayak and Sivarajan proposes and evaluates a measure for analysis of optical networks, namely absorption probability. Approximation methods are presented for estimating this measure for large networks, as an exact solution is computationally infeasible. The authors propose using this measure as an aid to network designers to assign capacities to the various links in the network, based on future predictions of the network load, the revenue generated by each successful connection, and the cost of upgrading the capacity on a link. This problem is also known as the "network dimensioning" problem. The second paper, by Antoniades *et al.*, presents a simulation approach for estimating the performance of metropolitan DWDM networks. Since full computer simulations of moderate to large size DWDM networks, accounting for all the possible impairments in the system, are impractical and time-consuming, the methodology outlined in the paper is a practical solution to a very complex problem. Such a practical approach can potentially be extremely valuable to the design and performance engineering of metropolitan dense WDM networks. The third paper, by Lee *et al.*, discusses a network design approach for a WDM network that employs a two-tier wavelength/waveband hierarchy and groups lightpaths together in wavebands according to their destinations. An ILP formulation as well as a heuristic are presented and analyzed. Utilizing wavebands is currently one of the areas of high interest for carriers and for equipment vendors that are developing all-optical (OOO) switches, as it leads to the usage of a reduced number of ports on the OOO switches. The fourth and fifth papers, authored by Eilam *et al.* and Calinescu *et al.*, both address the important problem of arranging a set of lightpath demands in rings so as to protect them via efficient ring protection. Both papers presented very similar and independent results. We, therefore, decided that both papers merit publication. The authors show that the design problem is NP-complete for a class of topologies and that it cannot be approximated. They also provide an algorithm for the design problem and its worst case behavior. While a great deal of interest today is centered around mesh restoration, much of the near-term deployment of optical networks, especially in the metro space, is still focused on ring protection. The problem chosen by the authors is thus very suitable to address network design issues for these networks.

The final section of the special issue covers the areas of Quality of Service (QoS), packet switching, and performance analysis. The first paper in this section is authored by Callegati *et al.* and it presents an optical packet switch architecture, based on multistage fiber delay lines (FDL), that handles packets of variable length with some level of QoS. Three options for the organization of the wavelength converters are described and simulation is used to calculate the packet loss probability for these architectures. The second paper, by Srinivasan and Somani, develops an approximate analytical model for computing blocking probabilities in optical networks that employ both time and space switching. This is done using a generalized switch/network model that allows modeling of different types of optical switching nodes. This paper offers valuable insight for combined performance analysis and potentially for the design of networks consisting of heterogeneous network elements. Finally, the last paper of this issue, by Bengi and van As, discusses a WDM ring network operated in a slotted way, where the nodes utilize tunable transmitters and fixed receivers (TT/FR). Different buffer selection strategies are compared analytically and by simulation. The paper also proposes a QoS enabling media access control (MAC) extension for the slotted WDM rings with TT/FR node architectures.

We received 82 submissions to this special issue, 18 of which were accepted. Unfortunately, because of the large number of submissions we were not able to accommodate many quality papers. In a number of cases, excellent papers that were deemed to be outside the scope of this issue were referred to other journals for publications. We wish to thank all authors for their submission to our special issue. For each paper we obtained at least three reviews, for a total of over 250 reviews! Accomplishing this task would have been impossible without the timely help of nearly 120 dedicated reviewers who provided expert and high quality reviews and offered valuable comments and suggestions to the authors. A special thanks goes to the reviewers for their great effort. The high quality of the special issue is a direct result of their critical reviews and valuable suggestions. Finally, we would be remiss if we did not extend a thank you to the IEEE publication staff and the JSAC Board representatives for all their help in publishing this special issue. In particular, we would like to thank Sue McDonald and Jeff Cichocki for their tireless efforts and valuable assistance in putting this issue together in a timely fashion.

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Dr. Qiao received the Andrew-Mellon Distinguished doctoral fellowship award from the University of Pittsburgh. He is also the founder and chair of the recently established Technical Group on Optical Networks (TGON) sponsored by SPIE. In addition, he is the IEEE Communication Society's Editor-at-Large for optical networking and computing, an editor of IEEE/ACM TRANSACTIONS ON NETWORKING, the *Journal on High-Speed Networks*, and the *Optical Networks Magazine*. He chaired and co-chaired the program section on IP over WDM at the Asia-Pacific Optical and Wireless Communications (APOC)'2001, the program on Optical Layer and Internetworking Technology in 2000, and the annual All-Optical Networking Conference from 1997 to 2000. He is also a Program Vice Co-Chair for the 1998 International Conference on Computer Communications and Networks (IC3N), and the expert panelists, technical program committee members and session organizers/chairs in several other conferences and workshops.

Debasish Datta (M'99) received the B.Tech degree in radiophysics and electronics from the Institute of Radiophysics and Electronics, Calcutta University, India, in 1973, and the M. Tech. and Ph.D. degrees in electronics and electrical communication engineering from the Indian Institute of Technology (IIT), Kharagpur, India, in 1976 and 1987, respectively.

From 1976 to 1978, he worked as an Assistant Executive Engineer in the Transmission R&D Division, Indian Telephone Industries Ltd., Bangalore. Since 1978, he has been engaged in research and teaching in the broad area of telecommunications and networking in the Indian Institute of Technology, Kharagpur, with specific research interest in the area of optical communication systems and networks. At present, he is a Professor in the Department of Electronics and Electrical Communication Engineering and also serves as the Chairman in the G. S. Sanyal School of Telecommunications at IIT Kharagpur. During the period between 1980 and 1981, he worked as Production Manager at Philips (India) Limited, Calcutta. From 1992 to 1993, he visited Stanford University, USA, on a one-year sabbatical to carry out research in the Department of Electrical Engineering on the impact of fiber nonlinearities on coherent optical communication system. From 1997 to 1998 and then in the summer of 1999, he visited University of California, Davis, to carry out research in the Department of Computer Science in the area of wavelength-division multiplexed (WDM) optical networks. His current research interests include wavelength-routed optical networks, optical access networks using WDM, IP over WDM, and wireless networks.

Georgios Ellinas (S'93–M'98) received the B.S, MS, and Ph.D. degrees all in electrical engineering from Columbia University, New York, NY, in 1991, 1993, and 1998, respectively.

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Dr. Ellinas was awarded a Fulbright fellowship (1987-1991) for undergraduate studies at Columbia University.

Andreas Gladisch (M'00) was born in Germany 1960. In 1986 he received the Dipl.Ing. degree from the Technical University of Ilmenau in theoretical electrotechnics. From 1986 to 1990 he was engaged in research on coherent optical communication and optical frequency control at Humboldt University Berlin, where he received the Ph.D. degree in optical communication.

He joined the Research Institute of Deutsche Telekom in 1991 where he was involved in projects with coherent optics, wavelength division multiplexing systems, wavelength control and frequency stabilization. From 1996 to 1998, he was head of a research group working in the field of design and management of optical networks and in 1999 he became the Head of the Network Architecture Department of T-Nova, the research and development subsidiary of Deutsche Telekom. He participated in several European Research Projects, for example ACTS-Meton, ACTS-Demon, ACTS-Moon, and EURESCOM P918 where his work was focused on IP-WDM integration, functional network architecture of optical networks, and management requirements. He has authored or co-authored more than 50 national and international technical conference or journal papers.

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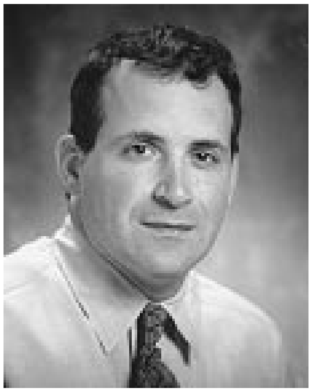

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