Guest Editorial Protocols and Architectures for Next Generation Optical WDM Networks

I. Introduction

OPTICAL wavelength division multiplexed networking, offering potential capacity in the multiterabits-per-second range, is poised to be a critical component of the next-generation Internet network infrastructure. There is significant research and commercial interest in making this a reality. WDM line systems already cover the globe, and attention is now turning toward addressing the practical issues of WDM-based local and metropolitan area networks, and the implications of using WDM on the next generation Internet backbone. At present, we are moving toward rapidly achieving the physical devices necessary to build commercially viable WDM networks. There are several fundamental research questions to be answered on a variety of topics, including switch and router architectures, protection and survivability mechanisms, quality of service support and scheduling algorithms, efficient routing and wavelength assignment algorithms.

The issue presented before you is a collection of high-quality papers addressing the critical issues surrounding the next generation of WDM networks.

II. Survey

In the invited paper, "WDM Optical Communication Networks: Progress and Challenges," Mukherjee presents a tutorial summarizing the research directions in WDM optical networks, the progress of WDM research, and a brief introduction to exciting new physical layer developments that impact networking layers.

III. Switching and Control Architectures

This set of papers deals with different aspects of switching and control architectures.

The SONET/SDH framing structure is often considered to be cumbersome for use in data transmission in optical networks. The paper, "A Simple Data Link (SDL) Protocol for Next Generation Packet Networks," by Doshi *et al.* proposes a unique and flexible framing mechanism for high speed optical links. The proposed mechanism is shown to provide a number of improvements upon the use of conventional framing techniques, e.g., reducing the possibility of error multiplication and increasing link efficiency. The paper by Xiong *et al.*, "Control Architecture in Optical Burst-Switched WDM Networks," presents the basic concepts for optical burst switching (OBS) and a general architecture of optical core routers and electronic routers. Some of the key design issues are discussed, and a new scheduling algorithm with performance results is reported.

The design and analysis of cross-connect architectures, that are based on power-efficient design principles, for multicast switches are presented in the paper, "Power-Efficient Design of Multicasting Wavelength-Routed Networks," by Ali and Deogun. In the paper, "A Novel All-Optical Transport Network with Time-Shared Wavelength Channels," Huang *et al.* propose a new optical switch architecture based on a time-wavelength-space routers (TWSRs) structure, in which a time-slot based lightpath is set up for a given source destination pair, and packets are routed based on the incoming port and the transporting wavelength in a slot-by-slot fashion. The paper by Li *et al.* introduces an in-band signaling protocol, called the sampling probe algorithm for use in packet switched DWDM networks. The protocol is reservation based, supporting a train of packets that results in higher throughput.

IV. Network Survivability and Fault Management

The next set of papers deals with network survivability and fault management, which are critical to successful network operation.

In the paper, "Optical Layer Survivability—An Implementation Perspective," Gerstel and Ramaswami discuss optical layer protection techniques. They study the factors that affect the complexity of optical protection schemes, and look at how protection schemes in the client and optical layers can work together in efficient ways. In the paper, "An Efficient Algorithm for Localizing Hard and Soft Failures in WDM Networks," Mas and Thiran study the problem of localizing faults in a network down to the root cause of a failure that can manifest itself in a multitude of other failures. This paper provides a novel, systematic fault localization framework for multilayer networks, and is expected to affect how faults are localized in real networks.

Transmission engineers often use rules of thumb such as four times the capacity for two-and-a-half times the cost. DWDM, with its inherent huge capacity, may well result in significant economies of scale. In the paper, "Influence of Modularity and Economy-of-Scale Effects on Design of Mesh-Restorable DWDM Networks," Doucette and Grover show, using operations research techniques, that taking modularity and economy-of-scale into account when designing WDM networks can result in cost savings and even topology reduction.

Automatic protection switching schemes are common in today's SDH/SONET networks. The paper by Ellinas *et al.*, "Protection Cycles in Mesh WDM Networks," shows how to

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apply such schemes to arbitrary mesh topologies in optical networks. The authors provide algorithms that network designers can use to derive the required protection cycles. Networks often utilize protection or restoration schemes in more than one layer, and this will be the case for next-generation IP networks running on top of WDM. The paper by Stamatelakis and Grover, "IP Layer Restoration and Network Planning based on Virtual Protection Cycles," introduces an extremely fast IP restoration technique for recovery from IP link and node failures which can be used in conjunction with WDM restoration techniques that recover from physical span cuts.

The paper by Rubin and Ling,"Failure Protection Methods for Optical Meshed-Ring Communications Networks," examines the throughput performance of meshed rings under failure conditions for various protection schemes, and describes how to create protection subnetworks using a minimal number of wavelengths.

V. Network Design and Reconfigurability

The following papers present solutions to the problems of network design and reconfigurability.

A new approach to solving a very practical problem—minimizing the number (and cost) of SONET add/drop multiplexers (ADMs) in a WDM ring network—is presented in the paper, "Reducing Electronic Multiplexing Costs in SONET/WDM Rings with Dynamically Changing Traffic," by Berry and Modiano. The traffic is assumed to be dynamic, and the grooming is assumed to occur without the help of cross-connects. The novelty in their approach is that one starts with a fully populated network and removes ADMs from wavelengths. In the paper, "Dynamic Load Balancing in WDM Packet Networks with and without Wavelength Constraints," Narula-Tam and Modiano study the problem of reconfiguring the logical topology to minimize the maximum link load. In particular, they develop iterative algorithms for load balancing that track rapid changes in the traffic pattern, yet make small changes to the topology in order to minimize network disruption.

The paper, "Analysis and Design of Backbone Architecture Alternatives for IP Optical Networking," by Baroni *et al.* is one of the first papers to provide an analytical framework for the combined design of the optical backbone network and the IP routers that surround it. This analysis looks at several ways to connect routers on top of an optical layer and compares their cost and other differentiating characteristics. The paper, "Grooming of Arbitrary Traffic in SONET/WDM Rings," by Wan *et al.* tackles the grooming problem for a combined SONET/WDM ring network for dynamic traffic. The main novelty of the paper is that it adopts graph theoretic techniques for solving the problem, and comes up with proven approximation rations between their algorithms and the optimal solution.

VI. Testbed Related

The following papers describe research related to several optical WDM testbed activities.

In the paper, "HORNET: A Packet-Over-WDM, Multiple Access Metropolitan Area Ring Network," a description of the system design and experimental results from HORNET—an optical packet over WDM testbed built at Stanford University—are presented. Bianco *et al.* in their paper, "Network Controller Design for SONATA, a Large-Scale All-Optical Passive Network," describe algorithms that a centralized network controller can utilize to assign time and wavelength resources, in a way that avoids conflicts, to a large number of end-terminals in a national-scale passive optical network. The authors show that such a complex control problem is simplified by decoupling the time dimension from the wavelength dimension.

The problem of scheduling bursty traffic in distribution tree networks, such as those considered for the MIT ONRAMP optical testbed, is thoroughly studied in the paper,"Supporting Bursty Traffic with Bandwidth Guarantee in WDM Distribution Tree Networks," by Kam and Siu. The paper by Liu *et al.*, "A Scheduling Application for WDM Optical Networks," describes a distributed network management architecture that provides a centralized scheduling application for connection requests. The paper indicates how such an application utilizes performance and current network usage data combined with scheduling algorithms to provide traffic control and efficient resource allocation.

VII. Quality of Service and Scheduling

These papers consider problems related to quality of service architectures and related scheduling algorithms.

Jukan and van As present a generalized approach to supporting quality of service differentiation in wavelength-routed networks using a technique called service-specific wavelength-resource graphs, in the paper, "Service-Specific Resource Allocation in WDM Networks with Quality Constraints." The paper, "QoS Performance in IP over WDM Networks," by Yoo *et al.* addresses the issues of provision of QoS in WDM networks without buffers and traffic isolation. The authors proposed the notion of offset time with FDL to provide service differentiation by reducing the burst loss probability and delay for high priority traffic classes. The paper by Ma and Hamdi, "Providing Dynamic Quality-of-Service Guarantees on WDM Optical Networks," studies the problem of providing QOS guarantees for real time application streams with variable packet length in WDM networks. A systematic mechanism comprised of admission control, traffic regulation, and message scheduling is proposed. Analytical models as well simulations to validate the models are presented.

In the paper, "Optical Routing of Asynchronous, Variable-Length Packets," by Tančevski *et al.*, the implementation of IP optical routers is discussed with a focus on design and analysis of a scheduling algorithm that will help eliminate voids that a result of switching variable length packets. In the paper, "The Multitoken Interarrival Time (MTIT) Access Protocol for Supporting Variable Size Packets over WDM Ring Network," Fumagalli, Cai, and Chlamtac introduce a novel WDM multitoken ring access protocol based on token-interarrival time, instead of the conventional mechanism by controlling the token rotation time. This leads to a more or less uniform distribution of the tokens around the ring, and further reduces the average access delay and the number of parallel transmissions at a node. In the

paper, "Scheduling Multirate Sessions in Time Division Multiplexed Wavelength-Routing Networks," Subramaniam *et al.* consider the problem of assigning time slots and wavelengths to a given static set of multirate sessions so as to maximize network throughput. They present scheduling algorithms with provable worst-case bounds as well as a greedy heuristic that achieves near-optimal performance on average in ring topologies.

VIII. RWA Problem

The following papers study problems related to routing and wavelength assignment.

The routing and wavelength allocation problem has been extensively studied for ring networks. However, the paper, "On-Line Routing and Wavelength Assignment in Single-Hub WDM Rings," by Law and Siu is one of the first papers to use competitive analysis techniques to come up with schemes that efficiently use these restricted resources in a dynamic environment where connections come and go without *a priori* knowledge of their arrival process. The network is assumed to be a WDM access ring with a single hub. In the paper, "Computing Approximate Blocking Probabilities in Wavelength Routed All-Optical Networks with Limited-Range Wavelength Conversion," Tripathi and Sivarajan present analytic techniques for computing the blocking probabilities of all-optical paths with limited wavelength conversion.

In reality, most of the optical networks will use multiple fibers between nodes. The paper, "Dynamic Routing and Assignment of Wavelength Algorithms in Multifiber WDM Networks," by Xu *et al.* addresses the problem of dynamic routing and assignment of wavelength in a multifiber network. Two resource strategies based on layered-graph algorithms are proposed. Simulation results indicate that these algorithms yield better performance than some of the existing ones. Li and Somani present an analytical model for evaluating the blocking probability in multifiber networks in their paper, "A New Analytical Model for Multifiber WDM Networks." Their results indicate that a small number of fibers is sufficient to guarantee higher network performance.

In the paper, "Optimal Routing and Wavelength Assignment in WDM Ring Networks," Lee *et al.*, study the routing and wavelength assignment problem on WDM rings without wavelength conversion. They solve a linear relaxation of the problem using the column generation technique, and then apply the branch-and-price procedure to get an optimal solution.

Acknowledgment

The Guest Editors would first like to acknowledge the authors of the 79 submissions for having chosen this special issue to disseminate their research. Each paper received at least three written reviews including one from at least one Guest Editor, with some papers receiving four or more reviews. This would not have been possible without the tireless efforts of all the reviewers, who did a thorough and excellent job of completing the reviews in a short amount of time. The Guest Editors gratefully acknowledge their help. They also thank Dr. R. Ramaswami, the JSAC Representative for this issue, who responded with enthusiasm to frequent questions, and who ably guided the guest editors through the process. They acknowledge the help of the IEEE staff, and in particular, S. McDonald.

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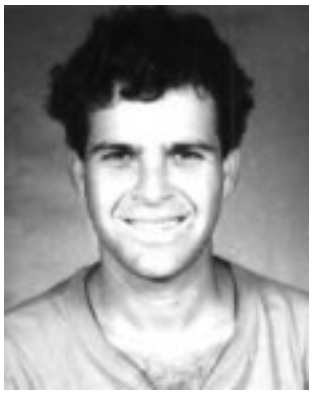

Ornan (Ori) Gerstel (S'95) received the B.A, M.Sc., and D.Sc. degrees from the Technion, Israel.

After finishing his D.Sc. degree, he joined the Optical Network Systems Group at IBM T.J. Watson Research Center and moved with the group to develop optical networking products with Tellabs Operations. There he served as the System and Software Architect for the Tellabs Optical Networking Group, building the TITAN 6100 metro DWDM product line. He left Tellabs to join Xros, a startup building all-optical cross-connects. He has served on the program committee of Infocom and OFC, and has published more than a dozen journal papers, and a similar number of patents. His research interests include network architecture, fault-tolerance and protection, and network design problems in optical networks.

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Bo Li (S'89—M'92—SM'99) received the B.S. (*summa cum laude*) and M.S. degrees in computer science from Tsinghua University, Beijing, China, in 1987 and 1989, respectively, and the Ph.D. degree in computer engineering from University of Massachusetts at Amherst in 1993.

Between 1994 and 1996, he worked on high performance routers and ATM switches in IBM Networking System Division, Research Triangle Park, NC. He joined the Faculty in the Computer Science Department, of the Hong Kong University of Science and Technology, in January 1996. His current research interests are: wireless mobile networking supporting multimedia, voice and video (MPEG-2 and MPEG-4) transmission over the internet, all optical networks using WDM.

Dr. Li has been on the Editorial board for IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS, Wireless Communications Series, *ACM Mobile Computing and Communications Review (MC2R), ACM/Baltzer Journal of Wireless Networks (WINET),* and *Journal of Communications and Networks (JCN)*. He has been Co-Guest Editor of special issues for IEEE COMMUNICATIONS MAGAZINE, IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS, and an upcoming *SPIE/Baltzer Optical Networks Magazine*. He has been involved in organizing numerous conferences, in particular for IEEE Infocom, since 1986, and is the Vice-Chair for Infocom 2001. He is a member of ACM.

Alan McGuire (M'98) was born in Falkirk, Scotland, in December 1964. He graduated from the University of St. Andrews with the first class honors degree in physics in 1987 and the M.Sc. degree in medical physics from the University of Aberdeen in 1998.

He joined BT from university and has been involved in a wide variety of technical areas including optical networking, SDH, ATM, network management, functional architecture, and network design. He was the manager responsible for network management and the data communications network for the initial rollout of WDM line systems in the BT network. He is active in international standards, and was a prime contributor to the development of the optical transport network architecture in the ITU-T. He is currently the Principal Engineer for core transport in the Advanced Communications Engineering Directorate of BT. He and his team provide support to BT, its Joint Ventures and Concert on all aspects of core transport. His current research interests are multilayer network design, digital wrapper technology, the application of functional architecture techniques to IP and dial-up wavelengths.

Mr. McGuire is a member of the Institute of Physics and is a Chartered Physicist.

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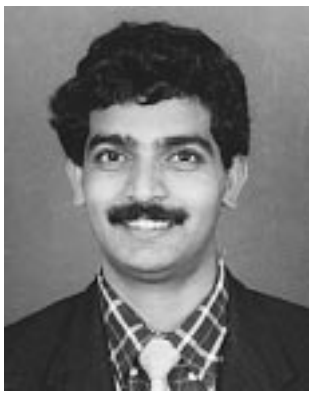

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Dr. Sivalingam has served on several conference Program Committees including Opticom 2000, ACM Mobicom 99, MASCOTS 99, and IEEE INFOCOM 1997. He has published an edited book on optical WDM networks in 2000. His work is supported by NSF, AFOSR, Cisco, Bellcore, Alcatel, and Washington Technology Center. He is a member of ACM.

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