Guest Editorial High-Performance Optical Switches/Routers for High-Speed Internet

I. Introduction

THE PHENOMENAL growth in the Internet traffic has spurred the integration of data networking and optical networking to support the high-speed Internet. The push for integrated Internet protocol (IP) over wavelength division multiplexing (WDM) has given new and strong incentives for optical packet/burst switching and hybrid optical electronic switches/routers, as well as different classes of network infrastructures.

This special issue is a collection of high-quality papers, dealing with state-of-the-art design and analysis of high-performance optical packet/circuit/burst switches and routers, and their influence on the operation and functionality of network infrastructures.

II. Invited Paper

In the paper "Packet Switching Matrix: A Key Element for the Backbone and the Metro," Chiaroni presents different network scenarios for the backbone and the metro. The paper addresses the importance of an optical packet switching matrix. The required optical technologies are also described and highlighted with some practical realizations and validation results.

III. Network Architecture

As the use of dense wavelength division multiplexing (DWDM) technology offers transportation at Terabit/s rate in a single fiber, an efficient and flexible integrated optical network switching architecture becomes important. The following three papers provide some foresighted strategies on this issue.

In the paper "The European IST Project DAVID: A Viable Approach Toward Optical Packet Switching," researchers from industry and academia jointly propose a synchronous network architecture handling fixed-length packets. It includes optical ring metropolitan networks (MAN) and meshed wide-area network (WAN) connected by optical packet routers (OPR). DAVID is a pragmatic approach to exploit and combine optical and electronic technologies in the current state and tries to provide a path to optical packet switching (OPS).

In the paper "High-Performance Optical-Label Switching Packet Routers and Smart Edge Routers for the Next-Generation Internet," Yoo *et al.* suggest an architecture with optical-label-based all-optical-packet switching routers at the core and smart electronic routers at the edge. The edge router provides traffic shaping and the core router resolves contention in wavelength, time, and space domains. They cooperate effectively and simulations demonstrate reasonably low packet loss rates and low latency values.

In the paper "Resource Management in an Integrated Optical Network," Sohraby *et al.* propose a novel integrated optical network switching architecture. The concept of "network controller" is introduced for the purpose of signaling and intelligent control across legacy and optical networks. Some resource allocation methods are also investigated by analytical approximations, as well as simulation results.

IV. Switching and Routing

Compared to electronic switching, all-optical switching is still immature in functionality. Current switching schemes in WDM networks include wavelength routing, optical burst switching (OBS) and OPS. The following papers address some approaches to improve performance within different switching schemes.

The mismatched granularity between large and fixed wavelength channels and traffic flows may cause serious waste of bandwidth. In addition, the scarcity of wavelengths also limits the scalability of a wavelength-routed network. To overcome the above limitations, in the paper "Optical Networks with Hybrid Routing," Huang and Copeland propose a hybrid wavelength and subwavelength routing (HWSR) scheme. Large traffic demands use wavelength routing, while multiple small traffic demands are multiplexed into a single wavelength channel. Electronic switching is performed at the subwavelength level. The paper presents both a static optimization formulation and a dynamic heuristic of the HWSR problem.

In the paper "Hybrid Switching and P-Routing for Optical Burst Switching Networks," Chen and Wang work to improve the delay and loss performance in OBS. Virtual lightpaths are setup over physical hops to reduce the offset time needed, which is part of the packet delay. On the other hand, p-routing searches for routes that can most likely to minimize the chance of collision and loss. The studies show that hybrid switching and p-routing are complementary and dramatically improve the performance of OBS networks.

Wavelength band switching (WBS) is a relatively new paradigm which groups several wavelengths together as a band and switch the band using a single port whenever possible to reduce port count, the associated control complexity, and cost of optical cross connects (OXCs). In the paper "A Study of Waveband Switching with Multilayer Multigranular Optical Cross Connects," Cao *et al.* formulate an integer linear programming model to minimize the port count of an OXC with three layers (fiber, waveband, and wavelength) needed for

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given traffic demands in the offline case. An efficient heuristic algorithm called balanced path routing with heavy-traffic first waveband assignment (BPHT) is further presented. Simulations show WBS using BPHT is beneficial in multifiber networks and waveband granularity has a large effect on the performance of WBS networks.

V. Switch Design

In the paper "PetaStar: A Petabit Photonic Packet Switch," Chao *et al.* present a new petabit photonic packet switch architecture. PetaStar includes a three-stage Clos-network photonic switch fabric, and an electronically packet buffering at port controllers. A distributed algorithm c-MAC is performed to schedule the fabric. The authors claim with an internal speedup of 1.5, PetaStar with a switch size of 6400×6400 and total capacity of 1.024 petabit/s can be achieved at a throughput close to 100% under various traffic conditions.

The paper "Architecture and Performance of AWG-Based Optical Switching Nodes for IP Networks," proposes and compares different architectures of AWG-based optical switching node in terms of complexity and traffic performance. Bregni *et al.*, show that under reasonable assumptions on the offered IP traffic, the simplest of the new proposed structures outperforms the original one.

The paper "Design of Wavelength Converting Switches for Optical Burst Switching" studies the design of the wavelength converting switches that construct large OBS routers. Ramamirtham *et al.* map the routing problem for these switches to a combinatorial game. The design of the game board corresponds to the pattern of permutation used at the input sections of the switch and affects the performance of the switch. The performance based on several different permutation patterns is studied. The most available wavelength assignment algorithm is presented and may improve the throughput of the switch using the contiguous permutation pattern.

In the paper "A Scalable Design of Multigranularity Optical Cross Connects for the Next-Generation Optical Internet," the focus is to expand total switching capacity by using tiers of various types, i.e., lambda, waveband, or fiber switching. Ho *et al.* formulate the problem of routing and wavelength assignment (RWA) with tunnel allocation (RWAT) into a constraint programming (CP) process. The CP is simplified as two integer linear programming (ILP) processes that are performed sequentially. A heuristic approach is found and it achieves a very good approximation of the optimal solution.

VI. Optical Fabric Scheduling

Utilizing optical technologies to build packet switching fabrics for high-capacity switches and routers has advantages in scalability, high bandwidth, power consumption, and cost. However, reconfiguration times of optical crossbars are much longer than those of electronic fabrics and prohibit the use of traditional scheduling algorithms. The basic idea is to slow down the scheduling frequency to reduce the reconfiguration overhead.

In the paper "Scheduling Algorithms for Optical Packet Fabrics" by Kar *et al.*, the scheduling unit is "envelope," which is an aggregation of multiple packets. The two-level hierarchical scheduler first schedules dummy envelopes and then sends out packets in the corresponding envelopes. Using proper scheduling algorithms, this scheme provides system stability, as well as bandwidth and delay guarantees, which are almost similar to that of output queued switches.

Another approach to reduce the scheduling rate is time slot assignment (TSA) scheme, which is used in the paper "On Scheduling Optical Packet Switches With Reconfiguration Delay." Li and Hamdi formulate an optical switching scheduling (OSS) problem. The paper overcomes the previous assumption on zero or infinite reconfiguration assumption and proposes ADJUST algorithm, which self-adjusts medium reconfiguration delay and other system parameters.

VII. Traffic Grooming

Since the cost of SONET add-drop multiplexers (SADM) at each node dominates the total cost of these networks, how to assign the wavelength, groom the traffic, and bypass the traffic through the intermediate nodes has received a lot of attention recently. Traffic grooming combines different low-speed traffic streams into high-speed traffic streams and tries to minimize the number of SADMs.

In the paper "Dynamic Traffic Grooming Algorithm for Reconfigurable SONET Over WDM Networks," Zhang and Ramamurthy propose a dynamic traffic grooming algorithm to reconfigure the wavelength assignment according to the new traffic pattern without disrupting the old traffic assignment. Two cases, best-fit and full-fit, are studied. Two heuristic algorithms [tabu search (TS-1) and two-phase TS-2] are presented for each case. The tabu-search algorithm is demonstrated to be more stable than the simulated annealing algorithm proposed in previous work.

Zhu *et al.* present four optical grooming OXC architectures and compare their characteristics under a dynamic traffic environment in the paper "A Comprehensive Study on Next-Generation Optical Grooming Switches." Three grooming schemes and two corresponding algorithms [grooming using auxiliary graph (GUAG) and grooming using light-tree (GULT)] are proposed for the grooming OXCs. The results show that the connection bandwidth-granularity distribution has a large impact on network throughput and network resource efficiency.

VIII. Optical Burst Switching (OBS)

OBS has become a research field of its own. In addition to the two previous papers on OBS described in Sections III and IV, respectively, this special issue includes three additional papers on OBS.

In the paper "Performance Analyses of Optical Burst Switching Networks," Rosberg *et al.* provides a scalable framework for analysis and performance evaluation of OBS networks. Most known OBS reservation policies such as just-enough-time (JET), just-in-time (JIT), burst segmentation, and route-dependent priorities are covered. A new reduced-load fixed-point approximation model is used to evaluate blocking probabilities in OBS networks. Simulations of the NSFNET network verify the accuracy of the model.

The paper "Prioritized Burst Segmentation and Composite Burst Assembly Techniques for QoS Support in Optical Burst-Switched Networks" introduces the concept of prioritized contention resolution and composite burst assembly. The scheme, proposed by Vokkarane *et al.* allows high-priority bursts to preempt low-priority bursts and enables full class isolation between bursts of different priorities in the core. At the edge of the network, a composite burst assembly technique combines packets of different classes into the same burst, placing lower class packets toward the tail of the burst. Packets at the tail of the burst are more likely to be dropped than packets that are placed at the head of the burst. Analysis and simulation show that significant differentiation with regard to packet loss and delay can be achieved.

In the paper "FRR for Latency Reduction and QoS Provisioning in OBS Networks," Liu *et al.* propose an aggressive forward resource reservation (FRR) at network ingresses to facilitate the end-to-end burst delay reduction functionality. Linear predictive filter (LPF)-based methods are investigated to effectively predict dynamic burst length. The FRR scheme has also been extended to facilitate quality-of-service (QoS) differentiation at network edges. The authors demonstrate FRR scheme yields a significant delay reduction for time-critical traffic without incurring a deleterious bandwidth overhead.

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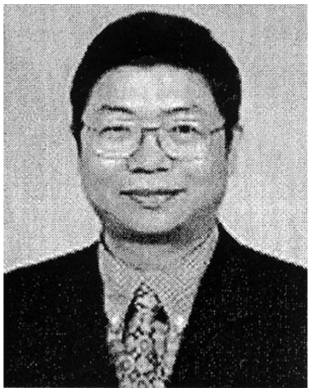
He has been a Faculty Member in the Department of Computer Science, Hong Kong University of Science and Technology, since 1991, where he is now Associate Professor of computer science and the Director of the Computer Engineering Program that has some 350 undergraduate students. From 1999 to 2000, he held Visiting Professor positions at Stanford University, Stanford, CA, and the Swiss Federal Institute of Technology, Zürich, Switzerland. His general areas of research are in high-speed packet switches/routers and all-optical networks, in which he has published more than 180 research publications, received numerous research grants, supervised some 20 postgraduate students, and for which he has served as Consultant to various international companies. Currently, he is working on high-speed networks including the design, analysis, scheduling, and management of high-speed switches/routers, wavelength division multiplexing (WDM) networks/switches, and wireless networks. He is currently leading a team that is designing one of the highest capacity chip sets for Terabit switches/routers. This chip set is targeted toward a 256×256 OC-192 switch and includes a crossbar fabric chip, a scheduler/arbiter chip, and traffic management chip.

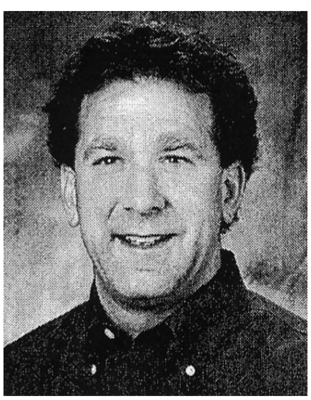
Dr. Hamdi was on the Editorial Boards of the IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE C*ommunication Magazine*, *Computer Networks*, *Wireless Communications and Mobile Computing*, and *Parallel Computing* and has been on the program committees of more than 50 international conferences and workshops. He was a Guest Editor of IEEE *Communications Magazine*, the IEEE JOURNAL ON SELECTED AREAS OF COMMUNICATIONS, and *Optical Networks Magazine* and has Chaired more than five international conferences and workshops, including the IEEE GLOBECOM/ICC Optical Networking Workshop, the IEEE ICC High-Speed Access Workshop, and the IEEE IPPS HiNets Workshop. He is the Chair of IEEE Communications Society Technical Committee on transmissions, access, and optical systems and Vice Chair of the Optical Networking Technical Committee, as well as ComSoc Technical Activities Council. He received the Best Paper Award out of 152 papers at the International Conference on Information and Networking in 1998. In addition to his commitment to research and professional service, he is also a dedicated teacher. He received the Best 10 Lecturers Award (through university-wide students voting for all university faculty held once a year) and the Distinguished Teaching Award from the Hong Kong University of Science and Technology. He is a Member of ACM.



H. Jonathan Chao (F'01) received the B.S. and M.S. degrees in electrical engineering from the National Chiao Tung University, Hsinchu, Taiwan, R.O.C., and the Ph.D. degree in electrical engineering from The Ohio State University, Columbus.

He is a Professor of electrical and computer engineering at Polytechnic University, Brooklyn, NY, where he has been since January 1992. He has been doing research in the areas of terabit switches/routers, quality-of-service (QoS) control, optical networking, and network security. He holds more than 20 patents and has published over 100 journal and conference papers in the above areas. He has also served as a Consultant for various companies, such as Lucent, NEC, and Telcordia. He has been giving short courses to industry people in the subjects of SONET/ATM/IP/MPLS networks for over a decade. From 2000 to 2001, he was Cofounder and CTO of Coree Networks, Tinton Falls, NJ, where he led a team to implement a multiterabit MPLS switch router with carrier-class reliability. From 1985 to 1992, he was a Member of Technical Staff at Telcordia, Red Bank, NJ, where he was involved in transport and switching system architecture designs and ASIC implementations, such as the first SONET-like framer chip, ATM layer chip, sequencer chip (the first chip handling packet scheduling), and ATM switch chip. From 1977 to 1981, he was a Senior Engineer at the Telecommunication Labs of Taiwan performing circuit designs for a digital telephone switching system. He coauthored two networking books *Broadband Packet Switching Technologies* (New York: Wiley, 2001) and *Quality of Service Control in High-Speed Networks* (New York: Wiley, 2001).

Prof. Chao was elected Fellow of the IEEE for his contributions to the architecture and application of VLSI circuits in high-speed packet networks. He received the Telcordia Excellence Award in 1987. He is a corecipient of the 2001 Best Paper Award from the IEEE TRANSACTION ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY. He has served as a Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (JSAC) on the special topics of Advances in ATM switching systems for B-ISDN (June 1997), "Next-Generation IP Switches and Routers" (June 1999), and the recent issue on "High-Performance Optical/Electronic Switches/Routers for High-Speed Internet." He also served as an Editor for IEEE/ACM TRANSACTIONS ON NETWORKING from 1997 to 2000.



Daniel J. Blumenthal (F'03) received the B.S.E.E. degree from the University of Rochester, Rochester, NY, in 1981, the M.S.E.E. degree from Columbia University, New York, NY, in 1988, and the Ph.D. degree from the University of Colorado at Boulder in 1993.

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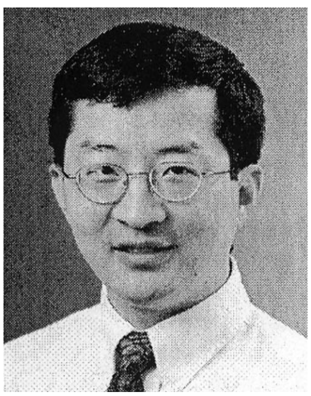
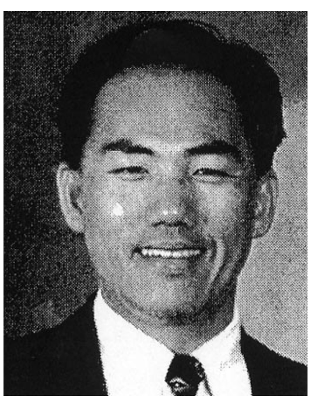
Dr. Leonardi received the "IEEE TCGN Best Paper Award" for a paper presented at IEEE GLOBECOM 2002, "High-Speed Networks Symposium." He has participated in the technical program committees of several conferences, including IEEE INFOCOM and IEEE GLOBECOM.



Chunming Qiao (S'89–M'93) is currently an Associate Professor with the State University of New York (SUNY) at Buffalo, Buffalo, NY, where he directs the Lab for Advanced Network Design, Evaluation, and Research (LANDER). He has published more than 100 papers in leading technical journals and conference proceedings and is recognized for his pioneering research on optical Internet and, in particular, the optical burst switching (OBS) paradigm. His work on integrated cellular and *ad hoc* networking systems (iCAR) is also internationally acclaimed.

Dr. Qiao is an Editor of several journals and magazines including IEEE/ACM TRANSACTIONS ON NETWORKING (ToN) and IEEE *Optical Communication*, as well as Guest Editor for several issues of IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS and other publications. He has Chaired and Co-Chaired many conferences and workshops including the Symposium on Optical Networks at ICC 2003 and OPTICOMM 2002. He is also the Founder and Chair of the Technical Group on Optical Networks (TGON) sponsored by SPIE and a Vice Chair of the IEEE Technical Committee on Gigabit Networking (TCGN).



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