4

Routed Wavelength WDM Networks

Lixin Wang and Mounir Hamdi
Hong Kong University of Science and Technology,
Kowloon, Hong Kong

1 INTRODUCTION

An optical fiber can potentially have more than 30 THz of bandwidth that can be exploited by future generation broadband ISDN networks. However, because of the mismatch between optical transmission and electronic processing, the network transmission rate cannot exceed few Gbps. One popular solution to this problem is to employ *wavelength division multiplexing* (WDM) by fragmenting the whole bandwidth of the optical fiber into a number of narrow band (say, 1 Gbps) channels. The source party can communicate with its destination party through these channels under the control of a given protocol.

In WDM networks, there are essentially two types of architectures, *passive switch networks* and *active switch networks*. A passive switch network uses a passive star coupler to split the inlet lightwave to all other outlets. Because the passive star coupler can be considered as a broadcasting device, this single-hop system is known as a broadcast and select WDM network [7]. In this type of system, network-wide status and control information can be easily obtained. As a result, through proper scheduling, the channel efficiency can be considerably high. In addition, due to the accuracy of the control information, a given quality-of-service (QoS) can be controlled and guaranteed relatively easy. However, to make a complete connection, the transceivers on each node have to frequently tune among the channels. Therefore the performance of this type of network is very sensitive to the network parameters, such as the number of channels, the number of nodes in the network, and the transmission overhead (e.g., transceiver tuning time). These restrictions can hamper the scalability of the network [7,31,32]. These problems can be overcome by using *strong multihop* systems [10]. Note that we can have a *weak multihop system*, which uses a *broadcasting and selection* scheme for its nodes to communicate but the network is organized in a multihop way. This approach can be used to reduce the tuning effect and adapt to the case where the transceiver tuning range is small [7]. However, this solution does not result in a scalable network system. The details of weak multihop WDM networks are out of the scope of this paper, and we will exclude this type of network when we introduce *multihop* networks in the rest of the paper.

In a multihop WDM system, the nodes are connected by relatively static channels. A pair of source and destination nodes may have to transmit packets through some intermediate nodes. Instead of working in a *broadcast and select* manner as in single-hop WDM systems, the nodes in a multihop system operate using a *store-and-forward* scheme. Upon arrival to an intermediate node, packets from an inlet link are buffered and then forwarded out according to a given *routing strategy*. As a result, most tuning operations are avoided (tuning may still be necessary when the network needs to be reconfigured). Because the connections between any two nodes can span through different paths, potentially the network capacity increases as the number of nodes increases. Hence the network can very scalable. However, an irregular network topology, an asymmetric traffic load, or a nonadaptable routing algorithm may cause congestion on some intermediate nodes [32]. The congestion causes considerable uncertainty in terms of packet delay, packet loss, inefficiency of network utilization, and complexity of network control. More importantly in these WDM networks, the buffering operations, which are currently implemented using electronic devices, strictly limit the optical bandwidth utilization. This results in an opto-electronic bottleneck problem.

The combination of a single-hop system and a multihop system, by employing a *wavelength routing switch* (WRS), results in a more efficient architecture, known as *wavelength routed optical network* (WRON), which is the main theme of this paper. This optical network employs wavelength multiplexers and optical switches in the routing nodes, so that any arbitrary topology can be accomplished, and very large areas can be covered. Nodes can obtain ‘‘single-hop’’ access in a WRON by setting up an all-optical *lightpath* through one or more WRS. Along the lightpath, packets are transmitted using identical wavelengths, without any optical-electronic conversion. Certain store-and-forward nodes can be used to conjunct two or more different lightpaths. The wavelength of these lightpaths are not necessarily the same. Thus if we think of the group of nodes that are connected by a lightpath as a *supernode*, the WRON can be treated as a multihop network of the supernodes. Theoretically, every node in the network can be involved in one or more lightpaths, at the same time. By properly designing *wavelength routing and assignment* (WRA) schemes, a WRON can be very scalable and flexible. On the other hand, efficient routing and network control and management that are needed in these networks are very challenging and present interesting issues that need to be solved.

In a WRON, a lightpath exclusively takes one of the wavelengths that are possibly used by all nodes connected in the path. Otherwise, different lightpaths may use the same wavelength at the same routing node, which leads to transmission conflicts. This is known as a *wavelength-continuity constraint*. By routing through a store-and-forward node, we can ‘‘change’’ the wavelength. However, a buffering operation has to be performed that may cause additional delay. The solution to this problem is to use a *wavelength conversion*. By adding a wavelength conversion device into a WRS, the switch becomes a *wavelength convertible routing switch* (WCRS). By applying this technique, several lightpaths with different wavelengths can be chained together, forming an all-optical path termed a *semilightpath*. With a semilightpath, a wavelength in the network can be reused, and the network utilization can be increased.

Because of the combined advantages and flexible features as well as the great potential connecting capability of the WRON, more and more researchers are interested in this subject, and many excellent works are published in the literature. This was the driving force behind writing this paper. In this paper, we survey the recent research related to wavelength routed optical networks that may serve as a good starting point for researchers starting to explore this interesting area.

The rest of the paper is organized as follows. Section 2 surveys the essential issues related to the design and operation of wavelength routed optical networks without wavelength conversion. Section 3 focuses on the special issues raised when employing wavelength convertible routing optical networks. Section 4 discusses QoS issues related to wavelength routed optical networks. Section 5 introduces multicasting on wavelength routed optical networks, and Sec. 6 concludes the paper.

2 WAVELENGTH ROUTING WDM NETWORKS

This section discusses the major issues that need to be considered when designing wavelength routing WDM networks without wavelength conversion.

2.1 Virtual Topology Mapping

Regular topology networks are well studied, and the routing on these networks is relatively simple and efficient. Therefore mapping a regular topology network onto the WRON can simplify the process of routing. Because the regular topology network is not physically implemented, we refer to *virtual topology*, while the WRON onto which the virtual topology is mapped is called a *physical network*. For example, hypercube networks can be a mapped onto a wavelength routing network such as NSFNET [32] to minimize the lightpath in terms of number of hops. A torus network can be mapped onto a WRON and the corresponding protocols of the torus can be easily applied, e.g., deflecting algorithm, slotted token grid protocol [39].

Suppose we are given a virtual topology $G_p = (V,E_p)$, where V is the set of network nodes, and E_p is the set of links connecting the nodes. Assume node i is equipped with a $D_p(i) \times D_p(i)$ wavelength-routing switch. For a network with M available channels and N nodes, the mapping of graph G onto the network can be described as (a) mapping each of the V nodes in G to the network ($V \leq N$) and (b) for each of the links in G, find a lightpath in the network so that the lightpath connects the two nodes and the lightpath takes the unique wavelength which is in the range of M. Performance of these mapped networks is evaluated in [22,26].

2.2 Routing and Wavelength Assignment (RWA)

We can address the routing problem in a more general sense. Given a *traffic matrix* that represents the source–destination pair of a connection and its required bandwidth, we construct sets of lightpaths so that the requirement of the traffic matrix can be satisfied. In fact there is usually more than one solution to this problem. This problem is known is the *routing and wavelength assignment* (RWA): to find an *optimal* solution from all possible solutions [30,29,11]. The *optimal* solution here can explained and applied in different aspects. The methods that find a minimum number of *hops* (the number of WRSs in a lightpath) are called *delay-oriented* optimization. Some algorithms attempt to find the maximum number of lightpaths that can be accommodated in a given network. This type of algorithm is known as a *utilization-oriented* optimization algorithm. In other algorithms, the cost, which includes the switches, amount of bandwidth, connection durations, etc., is taken into account for certain applications. This type of algorithm is known as a *cost-oriented* optimization algorithm. The first two types can be treated as special cases of the third one. But because the first two criteria are of special importance and application independence, they are typically considered separately. We can extend the concept to *QoS oriented* optimization algorithms where the cost is some function of QoS requirements and multimedia transmission overhead.

The RWA problem can be divided into two subproblems: the *routing problem* and the *wavelength assignment* problem. The routing problem is to construct a *virtual topology* that can optimally meet the requirement of the traffic. This problem can be formally described as follows [29]. Let λ_{sd} denotes the traffic (in terms of a lightpath) [23] from any source s to any destination d. Let F_{ij}^{sd} denotes the traffic that is flowing from source s to destination d on link *ij*. It can also be used to represent the *cost* of the traffic flow. The RWA problem can be described so as to *minimize* $F_{\max}$ where

$$F_{\max} \geq \sum_{s,d} F_{ij}^{sd} \qquad \text{for all } i,j$$

given the constraint

$$\sum_{i} F_{ij}^{sd} - \sum_{k} F_{jk}^{sd} = \begin{cases} -\lambda_{sd} & \text{if s} = j \\ \lambda_{sd} & \text{if d} = j \\ 0 & \text{otherwise} \end{cases}$$

where λ_{sd} and F_{ij}^{sd} are measured in terms of number of lightpaths.

This graph construction algorithm can be thought of as an integer linear programming (ILP) with the object function being to minimize the flow in each link. It is shown to be an NP-complete problem [6,23]. Suboptimal results can be obtained using *genetic*, *heuristic*, or hybrid methods [4,11].

Once the lightpaths are chosen, the wavelength assignment can be done by employing *graph coloring* algorithms, which are, again, NP-complete problems. Ramaswami and Sivarajan and Chen [18] and Banerjee and Chen [11] studied the upper and lower bounds of the connections that can be accommodated.

2.3 Dynamic Wavelength Routing

Given that the traffic matrix can be changed when the traffic patterns change, the RWA should generate different results that will lead to different wavelength assignments. Furthermore, if the physical network size and topology are unknown (this is a more realistic case in wide-area networks), an RWA may not be able to work properly due to the lack of global information. These cases need a *dynamic lightpath establishment* (DLE) ability. An early work on the topic is known as *Least Congested Path* (LCP) by Chan and Yum [38]. The idea is to keep the *spare route* as large as possible for a lightpath. When a new connection comes, LCP finds a path that least reduces the *spare route set*. In this way, the least congestion can be expected to be produced. More recent work is proposed by Harai et al. [26]. They consider a routing method with limited trunk reservation in which connections with more hops are prepared for more alternate routes. In addition, the performance improvement is investigated by introducing a wavelength assignment policy and a dynamic routing method. The effectiveness of the proposed method is investigated through simulation. Struyve and Demeester discussed different dynamic routing methods on various lightpaths [2]. They defined *nonprotection*, *dedicated protection*, and *shared protection* modes to deal with the coming calls according to different usage strategies of spare routes. Three routing strategies are analyzed which adopt the shortest path routing for *fixed minimum hop*, *dynamic minimum hop*, and *dynamic competitive* routing.

3 WAVELENGTH CONVERTIBLE ROUTED OPTICAL NETWORKS (WCRON)

A wavelength converter is a device that can *convert* the wavelength inlet from an input into another wavelength in the output. With this function of wavelength conversion, the lightpaths in different wavelengths can be chained, without an electronic store-and-forward process, into one optically connected route which is referred to as a semilightpath. This function solves the *wavelength continuity constraint* [28] and results in the capability of wavelength reuse, more flexibility, and higher utilization of network bandwidth. However, there are impacts that have to be considered in a WCRON.

The benefits obtained by using the wavelength conversion are referred to as *wavelength conversion gain*. Suppose a network has W wavelengths per link. Let ρ be the probability that a wavelength is used in any fiber link. For a lightpath in the network, there are H links. With wavelength conversion, a connection cannot be allocated only if all the W wavelengths in one of the H links are occupied, i.e., the blocking probability of the lightpath is

$$P_c = 1 - (1 - \rho^W)^H$$

Define q to be the utilization corresponding to the blocking probability P_c. Then

$$q = [1 - (1 - P_c)^{1/H}]^{1/W} \approx \left(\frac{P_c}{H}\right)^{1/W}$$

While in the wavelength routing networks without wavelength conversion, the connection is blocked when all the wavelengths are used, at least, in one of the H links. The blocking probability P_s is

$$P_s = [1 - (1 - \rho)^H]^W$$

and the corresponding utilization, p, is given by

$$p = \left[1 - (1 - P_s\left(\frac{1}{W}\right)\right]^{1/H} \approx -\frac{1}{H}\ln(1 - P_s^{1/W})$$

Thus the wavelength conversion gain G for the same blocking probability P is

$$G = \frac{q}{p} \approx H^{1-(1/W)} \frac{P^{1/W}}{-\ln(1 - P^{1/W})}$$

As can be seen, as W increases, also G increases until it gets to the peak around $W = 10$, where a maximum gain of $H/2$ is achieved. Generally, the larger the number of wavelengths (W) and the longer the lightpaths (H), the higher the wavelength conversion gain (G) would be.

3.1 Converter-Based Wavelength Routing Assignment

Under the assumption that any of the wavelengths can be converted to any other wavelength used in the network, Ramaswami and Sivarajan show that in case all the WRS are equipped with a wavelength converter, the WCRON is equivalent to a circuit-switching telephone network [18]. As a result, the wavelength routing problem becomes equivalent to a circuit-switching network routing problem. Thus all circuit-switching routing algorithms can be applied. However, not every routing node (WRS) necessarily has wavelength conversion ability due to the existence of the lightpath. To optimize the number of converters (WCRS) needed in a WCRON for-given number of wavelengths and number of nodes can be obtained by various types of algorithms [6,24].

Ramaswami and Sasaki study the case where there is a limited number of wavelengths that can be converted [45]. They investigate the ring, star, tree, mesh, and hub-based networks with fixed wavelength conversion capability in the nodes. They show that with the limited number of wavelengths that can be converted, the connection can still be efficiently routed.

3.2 Dynamic Wavelength Routing with Wavelength Conversion

There are a number of ways to implement wavelength converters, such as opto-electronic conversion, coherent effects, and cross-modulation [23,28]. Different implementation methods lead to different costs. Moreover, reconfiguration of the WCRS results in an additive delay and extra overhead. In a static wavelength routing network, these costs just occur once at the system initialization time, so they can be ignored. But in dynamic wavelength routing networks, the reconfiguration happens frequently, so the costs associated have to be taken into account. Chlamtac et. al. proposed a distributed *shortest path algorithm* to find the cost-effective path in a given routing network [30], which was later improved by Liang et al. [3] by separately considering the lightpath cost and the semilightpath cost. Karasan and Ayanoglu proposed a least-loaded routing algorithm that jointly selects the least-loaded routed-wavelength pair [1]. This algorithm produces a large wavelength conversion gain.

The dynamic routing approach can also be used to improve the reliability of the network services. When a routing node or a fiber link is broken, all related lightpaths or semilightpaths are in failure. By dynamic routing with wavelength conversion, locally reconfiguring some of the neighbor routing nodes can be achieved by passing the fault nodes or links without affecting other nodes.

4 QoS ISSUES ON WAVELENGTH ROUTING NETWORKS

The quality-of-service (QoS) provisioning is the idea that the transmission rates, error rates, and other characteristics can be measured, improved, and to some extent, guaranteed in advance. Different types of applications have different QoS requirements. Accordingly, a network should supply multiple levels of transmission services to meet the needs of various traffic streams. In the context of wavelength routing networks, the QoS can be measured in terms of *connection blocking probability*, i.e., the probability that a requested connection cannot find a route that satisfies the QoS requirement of the connection. However, the implication behind the probability can be varied as a function of the different traffic characteristics. For example, a video stream can be admitted if we found a lightpath that satisfied the bandwidth and delay jitter requirements for it. A file downloading request does not necessarily result in the establishment of a dedicated lightpath; a certain feasible route may be a multihop route, because usually the file transmission does not have very strict delay and bandwidth requirements. Although the QoS performance of these two types of traffic can be evaluated in terms of blocking probability, their resource occupation are obviously different. As a result, wavelength assignment strategies are different.

The QoS oriented wavelength routing problem can be formally described as follows [37]. Given a network $G(V,E)$, with a maximal rate R_l and a link delay d_l for each $l \in E$ and for each of the connections i, $1 \leq i \leq I$, where I is the connection set, and given the source s^i, destination t^i, burst δ^i, packet size c^i, delay constraint D^i, and bandwidth requirement b^i, then a *feasible path* p^i should satisfy

$$\frac{\delta^i + \text{hops}(p^i)c^i}{r^i} + \sum_{l \in p^i} d_l \leq D^i \qquad \text{for } \forall i$$

$$\sum_{i, l \in p^i} r^i \leq R_l \qquad \text{for } \forall l$$

$$r^i \geq b^i \qquad \text{for } \forall i$$

It is shown that for $I > 1$, this is an NP-hard problem.

As networks grow in size and complexity, full knowledge of the network parameters is typically unavailable. Hence routing must rely on partial or approximate information and still meet the QoS demands. Lorenz and Orda study the end-to-end delay guarantees for networks with uncertain parameters. They formulated two generic routing problems within the framework where the bandwidth can be reserved and guaranteed. They treat the problem as a maximum flow algorithm. They show that with a delay jitter constraint, the problem is NP-complete. A polynomial-time approximation algorithm is proposed [36].

Jukan and van As study the effects of the *quality attributes* on the routing approach and present simulation results [15]. Huang et al. study the isochronous path selection problem [14]. They show that given a set of established isochronous connections and a set of new isochronous requests, the problem of using a minimal amount of an isochronous bandwidth to serve this isochronous traffic, including the established connections and new requests, is NP-hard. They also propose an isochronous path selection algorithm based on paths merging and splitting.

5 MULTICASTING IN WAVELENGTH ROUTING NETWORKS

Various applications demand *group* communication, i.e., more than two parties are involved in an instance of communication. Since using point-to-point methods to implement this function may result in longer delays and extra network resources consumption, a more natural approach is usually considered in this context. That is to make the group of parties share the same communication channel so that one transmission operation can produce the packets for the rest of the members in the communication group, which is referred to as *multicasting*. In wavelength routing networks, the issues involved for multicasting are no longer to find a lightpath, which is usually represented by a point-to-point communication, but to find a subgraph in the network so that the shared communication channel can be established. To avoid multiple paths between any pair of parties in the group, the subgraph must be a tree. The minimization of the tree cost has traditionally been formulated as a *Steiner Minimal Tree* (SMT) [46,41], and the MST has been shown to be NP-complete.

Ramanathan presents a polynomial-time algorithm [41] that provides for tradeoff selection using a single parameter *k* between the tree cost (Steiner cost) and the run time efficiency. He involves a *directed Steiner Tree* (DST) to describe the wavelength routing network. Accordingly, the *Directed Steiner Minimal Tree* is obtained by the proposed algorithm, *Selective Closest Terminal First* (SCTF), which selects a set of vertices from a partially grown tree and adds a path to a terminal closest to this set.

Tridandapani and Mukherjee study the star-coupler-based multicasting problem [42] by developing a general analytical method for modeling such a system in the context of multicasting traffic. It appears that there is an optimal number of channels that balances the tradeoff of queuing delay and hop distance.

Rouskas and Baldine discuss the multicasting problem in the presence of delay constraints [43]. They show that the problem of finding a multicasting tree with delay constraints among end-to-end users is an NP-complete problem. They propose a heuristic method to solve the problem.

Lin and Lai [44] introduce a dynamic multicasting routing problem in which nodes are allowed to leave dynamically and join the communication group. Hence the multicasting becomes tailorable dynamically. In this algorithm, a virtual trunk (VT), which is a tree of the underlying graph, is introduced and is used as a template for constructing multicasting trees.

6 CONCLUSION

This chapter presents a survey about wavelength routing WDM networks. The topics covered are virtual topology mapping and static and dynamic wavelength routing and assignments, with and without wavelength conversion. The quality of service provision and multicasting in wavelength routing networks are also discussed. Although it is widely believed that wavelength routing networks will assume a very important role in the next generation of WAN/MAN systems, there are very few tutorial papers on this area. We hope that this chapter can be useful to researchers wanting to get a brief introduction into this area.

REFERENCES

1. E. Karasan and E. Ayanoglu. Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks. *IEEE/ACM Transactions on Networking*, Vol. 6, No. 2, pp. 186–196, April 1998.
2. K. Struyve and P. Demeester. Dynamic routing of protected optical paths in wavelength routed and wavelength translated networks. *ECOC 97*, 22–25, September 1997.
3. W. Liang, G. Havas, and X. Shen. Improved lightpath (wavelength) routing in large WDM networks. *Proceedings 18th International Conference on Distributed Computing Systems*, pp. 516–523, 1998.
4. M. C. Sinclair. Minimum cost routing and wavelength allocation using a genetic algorithm. Heuristic hybrid approach. *Sixth IEEE Conference on Telecommunications*, pp. 67–71, 1998.
5. O. Gerstel. On the future of wavelength routing networks. *IEEE Network*, Vol. 10, No. 6, pp. 14–20, Nov.-Dec. 1996.

6. T. K. Tan and J. K. Pollard. Determination of minimum number of wavelengths required for all-optical WDM networks using graph coloring. *Electronics Letters*, Vol. 31, No. 22, pp. 1895–1897, Oct. 1995.
7. R. Ramaswami. Multi-wavelength light-wave networks for computer communication. *IEEE Communication Magazine*, Vol. 31, No. 2, pp. 78–88, Feb. 1993.
8. R. J. et al. Cascading of a non-blocking WDM cross-connect based on all-optical wavelength converters for routing and wavelength slot interchanging. *Electronics Letters*, Vol. 33, No. 19, pp. 1647–1648, Sept. 1997.
9. E. A. Medova. Network flow algorithms for routing in networks with wavelength division multiplexing. *IEEE Proceedings on Communication*, Vol. 142, No. 4, pp. 238–242, Aug. 1995.
10. A. Bononi. Weakly versus strongly multihop space-division optical networks. *Journal of Lightwave Technology*, Vol. 16, No. 4, pp. 490–500, April 1998.
11. S. Banerjee and C. Chen. Design of wavelength-routed optical networks for packet switched traffic. *1995 IEEE International Conference on Communications*, pp. 444–448, 1996.
12. C. Chen and S. Banerjee. A new model for optimal routing and wavelength assignment in wavelength division multiplexed optical networks. *Proceedings IEEE INFOCOM '96*, pp. 164–171, 1996.
13. S. L. Danielsen, C. Joergensen, B. Mikkelsen, and K. E. Stubkjaer. Analysis of a WDM packet switch with improved performance under bursty traffic conditions due to tunable wavelength converters. *Journal of Lightwave Technology*, Vol. 16, No. 5, pp. 729–735, May 1998.
14. N. F. Huang, G. H. Liaw, and C. C. Chiou. On the isochronous paths selection problem in an interconnected WDM network. *Journal of Lightwave Technology*, Vol. 14, No. 3, pp. 304–314, March 1996.
15. A. Jukan and H. R. van As. Quality-of-service routing in optical networks. *11th International Conference on Integrated Optics and Optical Fiber Communications*, pp. 160–163, 1997.
16. E. D. Lowe and D. K. Hunter. Performance of dynamic path optical networks. *IEEE Proceedings: Optoelectronics*, Vol. 144, No. 4, pp. 235–239, Aug. 1997.
17. G. Venkatesan, G. Mohan, and C. S. R. Murthy. Probabilistic routing in wavelength-routed multistage, hypercube, and Debruijn networks. *Proceedings Fourth International Conference on High-Performance Computing*, pp. 310–315, 1997.
18. R. Ramaswami and K. N. Sivarajan. Routing and wavelength assignment in all-optical networks. *IEEE/ACM Transactions on Networking*, Vol. 3, No. 5, pp. 489–500, Oct. 1995.
19. R. Ramaswami and K. N. Sivarajan. Design of logical topologies for wavelength-routed optical networks. *IEEE Journal on Selected Areas in Communications*, Vol. 4, No. 5, pp. 840–851, June 1996.
20. Z. Zhang and A. S. Acampora. A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength reuse. *IEEE/ACM Transactions on Networking*, Vol. 3, No. 3, pp. 281–288, June 1995.
21. Z. Zhang, D. Guo, and A. Acampora. Logarithmically scalable routing algorithms in large optical networks. *Proceedings IEEE INFOCOM '95*, Vol. 3, pp. 1290–1299, 1995.

22. D. Guo, A. S. Acampora, and Z. Zhang. Hyper-cluster: a scalable and reconfigurable wide-area lightwave network architecture. *IEEE Global Telecommunications Conference*, pp. 863–867, 1997.
23. B. Mukherjee. *Optical Communication Networks*. McGraw-Hill Series on Computer Communications, McGraw-Hill, 1997.
24. K. C. Lee and V. O. K. Li. A wavelength-convertible optical network. *Journal of Lightwave Technology*, Vol. 11, No. 5–6, pp. 962–970, May-June 1993.
25. S. Subramaniam and R. A. Barry. Wavelength assignment in fixed routing WDM networks. *1997 IEEE International Conference on Communications*, pp. 406–410, 1997.
26. H. Harai, M. Murata, and H. Miyahara. Performance evaluation of routing methods in all-optical switching networks. *Trans. Inst. Electron. Inf. Commun. Eng*., Vol. J80B-I, No. 2, pp. 74–86, Feb. 1997.
27. A. Birman. Computing approximate blocking probabilites for a class of all-optical networks. *IEEE Journal of Selected Areas in Communications*, Vol. 14, No. 5, pp. 852–857, June 1996.
28. R. A. Barry and P. A. Humblet. Models of blocking probability in all-optical networks with and without wavelength changers. *IEEE Journal of Selected Areas in Communications*, Vol. 14, No. 5, pp. 858–867, June 1996.
29. D. Banerjee and B. Mukherjee. A practical approach for routing and wavelength assignment in large wavelength-routed optical networks. *IEEE Journal of Selected Areas in Communications*, Vol. 14, No. 5, pp. 903–908, June 1996.
30. I. Chlamtac, A. Farago, and T. Zhang. Lightpath (wavelength) routing in large WDM networks. *IEEE Journal of Selected Areas in Communications*, Vol. 14, No. 5, pp. 909–913, June 1996.
31. B. Mukherjee. WDM-based local lightwave networks, Part I. Single-hop system. *IEEE Network*, pp. 12–27, May 1992.
32. B. Mukherjee. WDM-based local lightwave networks, Part II. Multihop system. *IEEE Network*, pp. 20–32, July 1992.
33. A. Mokhtar and M. Azizoglu. In: G. Cameron, M. Hassoun, A. Jerdee, and C. Melvin. Adaptive techniques for routing and wavelength assignment in all-optical WANs. *Proceedings of the 39th Midwest Symposium on Circuits and Systems*, pp. 1195–1198, 1996.
34. L. Kleinrock, M. Gerla, N. Bambos, J. Cong, E. Gafni, L. Bergman, and J. Bannister. The supercomputer supernet: a scalable distributed terabit network. *Journal of High Speed Networks*, Vol. 4, No. 4, pp. 407–424, 1995.
35. E. Basturk, et al. Design and implementation of a QoS capable switch-router. *Proceedings Sixth International Conference on Computer Communications and Networks*, pp. 276–284, 1997.
36. D. H. Lorenz and A. Orda. QoS routing in networks with uncertain parameters. *Proceedings of INFOCOM ’98*, Vol. 1, pp. 3–10, 1998.
37. A. Orda. Routing with end to end QoS guarantees in broadband networks. *Proceedings of INFOCOM ’98*, Vol. 1, pp. 27–34, 1998.
38. K. M. Chan and T. P. Yum. Analysis of least congested path routing in WDM lightwave networks. *Proceedings IEEE INFOCOM ’94*, pp. 962–969, 1994.

39. M. Hamdi and L. X. Wang. All-optical MAC protocol for Gbits/sec fiber optic LANs/MANs. *Proc. SPIE*, Vol. 2919, pp. 297–305, 1996.
40. M. S. Borella and B. Mukherjee. Limits of multicasting in a packet-switched WDM single-hop local lightwave network. *Journal of High Speed Networks*, Vol. 4, No. 2, pp. 155–167, 1995.
41. S. Ramanathan. An algorithm for multicast tree generation in networks with asymmetric links. *Proceedings IEEE INFOCOM '96*, 1996, pp. 337–344.
42. S. B. Tridandapani and B. Mukherjee. Multicast traffic in multi-hop lightwave networks: performance analysis and an argument for channel sharing. *Proceedings IEEE INFOCOM '96*, pp. 345–352, 1996.
43. G. N. Rouskas and I. Baldine. Multicast routing with end-to-end delay and delay variation constraints. *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 3, pp. 346–356, April 1997.
44. H. C. Lin and S. C. Lai. VTDM—a dynamic multicast routing algorithm. *Proceedings IEEE INFOCOM '98*, pp. 426–432, 1998.
45. R. Ramaswami and G. G. Sasaki. Multiwavelength optical networks with limited wavelength conversion. *Proceedings IEEE INFOCOM '97*, pp. 489–498, 1997.
46. F. K. Hwang and D. S. Richards. Steiner tree problems. *Networks*, Vol. 22, pp. 55–89, 1992.