Intermediate-Node Initiated Reservation (IIR): A New Signaling Scheme for Wavelength-Routed Networks with Sparse Conversion

Kejie Lu †, Jason P. Jue †, Timucin Ozugur *, Gaoxi Xiao ‡, and Imrich Chlamtac †
† The Center for Advanced Telecommunications Systems and Services
The University of Texas at Dallas, Richardson, TX 75083
* Alcatel Research and Innovation Center, Plano, TX 75075
‡ School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore 639798

Abstract— **In this work, we propose a new distributed signaling scheme, within the GMPLS framework, for establishing lightpaths in wavelength-routed networks with sparse wavelength conversion. Analytical models are developed to evaluate the performance of the proposed scheme. Theoretical and simulation results show that compared to the classic scheme designed primarily for networks with no wavelength conversion, the proposed signaling scheme can achieve much lower blocking probability.**

I. INTRODUCTION

Wavelength division multiplexing (WDM) technology has been progressing steadily. Existing systems are now capable of providing a total of more than 1 Tbps bandwidth on a single optical fiber. To fully utilize these high data rates, all-optical connections, or *lightpath* [1], can be established between source and destination nodes. Lightpath-based optical networks are generally referred to as *wavelength-routed networks*.

Traffic in a wavelength-routed network may be static, in which case connections are known in advance and remain in the network semi-permanently, or traffic may be dynamic, in which connection requests arrive and depart over time. In this work, we will consider dynamic traffic, which is the natural setting for future networks.

To accommodate connection requests dynamically, a lightpath establishment scheme is required to find a route and assign a wavelength for the given connection request. This scheme can be either *centralized* or *distributed*. A centralized scheme may perform more efficiently when the network is small and the traffic is not bursty. However, a distributed scheme may be more appropriate for large optical networks and bursty Internet traffic. Distributed schemes have been proposed and are now being standardized within the framework of the *generalized multi-protocol label switching* (GMPLS) [2]. In this paper, we will focus on distributed control schemes.

A key performance figure in lightpath establishment is the connection blocking probability, the probability that an arriving connection request will be rejected. For a network in which all nodes have full wavelength conversion, a connection request will be accepted if every link in the path from source to destination has at least one available wavelength. On the other hand, in a network without wavelength conversion, a connection request will be rejected if a common wavelength cannot be found on the route between the source and destination, even though all links in the path may have available wavelengths. The constraint that a lightpath must use the same wavelength along the entire path is known as *wavelength continuity constraint* [1]. Although full wavelength conversion is desirable from a blocking perspective, it is difficult to implement due to the high cost of converters, which are expected to remain expensive in the near future [4]. A possible solution is to equip only a subset of nodes with converters. This approach is referred to as *sparse conversion*. The performance of sparse conversion in a centralized network has been studied in [5]; however, the performance in a distributed network, particularly within the GMPLS framework, has not been studied.

In this paper, we present a new signaling scheme, within the GMPLS framework, for establishing lightpaths in a wavelength-routed network with sparse conversion. Analytical models are proposed for evaluating the performance of the new scheme. Analysis and simulation results show that the proposed signaling scheme can significantly improve system performance in terms of blocking probability.

The rest of paper is organized as follows. In Section II, we elaborate on the Intermediate-Node Initiated Reservation (IIR) scheme. Analytical models are developed in Section III to evaluate the blocking performance of the proposed scheme. Numerical results are presented in Section IV. Section V concludes the paper.

II. INTERMEDIATE-NODE INITIATED RESERVATION (IIR)

In a GMPLS-based network, routing protocols such as *Open Shortest Path First with Traffic Engineering* (OSPF-TE) are used to exchange routing information, including topology and resource availability. Upon receiving a connection request, a route is calculated by using a constraint-based routing algorithm. Once the route is determined, a signaling scheme is responsible for establishing lightpaths. Candidates for the signaling protocol within the GMPLS framework include the *Resource reSerVation Protocol with TE* (RSVP-TE) and the *Constraint-based Routing Label Distribution Protocol* (CR-LDP). Regardless of which signaling protocol is used, there is no guarantee that the *updated global information* with respect to wavelength availability on each link will be available in a distributed environment. Link state information may become

0-7803-7802-4/03/$17.00 (C) 2003 IEEE

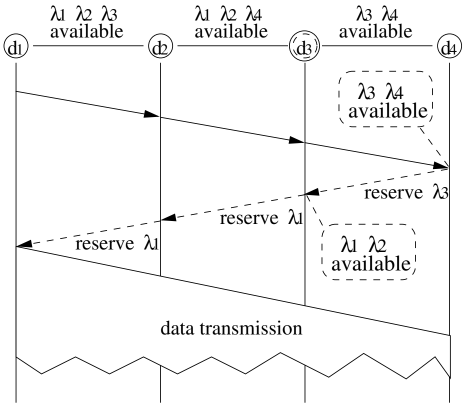

Fig. 1. An example of the classic DIR scheme.

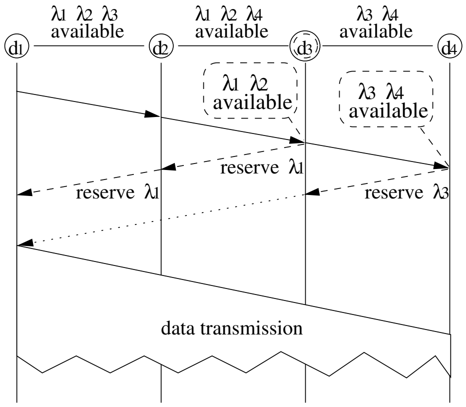

Fig. 2. An example of the IIR scheme.

outdated because the update messages are broadcast only periodically and also because it takes some time for the updates to propagate to a node. The problem of outdated information does not exist in centralized schemes.

A well-known distributed signaling method that can be supported by GMPLS networks is the *destination-initiated reservation* (DIR) method [3]. In the DIR method, a connection request is forwarded from the source to the destination, collecting the wavelength availability information of every link along the route. Based on this information, the destination node will select an available wavelength along the path (if such is available) and send a *reservation request* back to the source node to reserve the selected wavelength. Fig. 1 shows an example of the classic DIR method. We can see that, due to the existence of sparse wavelength conversion, different wavelengths may be reserved on different links of the path.

It has been shown that, in a network with no wavelength conversion, connection blocking due to outdated information may dominate the overall performance when the traffic load is low [6], [7]. This kind of blocking can also occur in a network with sparse conversion. For example, on the route as shown in Fig. 1, it is possible that when the reservation request reaches node d_2, it is found that λ_1 has been reserved by another reservation request which arrived earlier. It has been shown that connection blocking due to outdated information increases significantly with the round trip propagation delay between the link and the destination node [6], [7], i.e., the delay, denoted as *vulnerable period* hereafter, between the moment that the link state information is collected and the moment that the reservation request arrives.

To lower the connection blocking due to outdated information, we introduce a new signaling scheme, referred to as *Intermediate-Node Initiated Reservation (IIR)*, by exploiting the capability of conversion. An example of this scheme is shown in Fig. 2. We see that if the network has sparse wavelength conversion, we can separate every route into several *segments*, where the end nodes of each segment could only be the source node, the destination node, or a node with wavelength conversion capability. The primary observation is that the wavelength reserved in one segment can be totally independent of the wavelength reserved in another segment, due to the wavelength conversion capability at the end nodes of each segment. Therefore, a *segment reservation* request can be issued at the end-node of a segment once the connection request reaches that node. Finally, when the connection request reaches the destination node, a *primary reservation* message is sent back to reserve wavelength on the last segment and to inform the source node of the status of the lightpath establishment.

By using this strategy, the vulnerable period for reserving a wavelength on a link is reduced to the round trip propagation delay between current node and the downstream end node of the segment. Thus, blocking due to outdated information can be reduced. However, while the vulnerable period becomes smaller, some network capacities will be reserved for slightly longer time before data transmission begins (See Fig. 2), which will increase the blocking in the forward direction. To evaluate the performance of the proposed signaling scheme, we propose two blocking analysis models for the classic DIR method and the IIR scheme, respectively. Both the analysis and simulation results show that the improvement in the backward direction significantly outweighs the slight drawback in the forward direction. As a result, the overall blocking probability is significantly lowered, as we will see in Section III and IV.

To implement the IIR scheme, current signaling protocols have to be extended to enable the initiation of reservation from an intermediate node. The detailed discussions on such extensions, however, are beyond the scope of this paper.

III. THEORETICAL ANALYSIS

In this section, we propose blocking analysis for both the classic DIR method and the new IIR scheme. To simplify our analysis, we make the following assumptions:

- The network is composed of J links connected in an arbitrary topology.
- Each link is composed of C wavelength channels.
- Wavelength conversion is available only at a certain given set of nodes.
- Besides the two end nodes of a segment, no other node in a segment has converters.

- The connection requests for each pair of source-destination nodes arrive from a Poisson process with an arrival rate λ_R, where R denotes the fixed route between the two nodes.
- Connection holding time is exponentially distributed with parameter μ.
- The wavelength assignment policy is random selection.

A. Framework

For both the classic and the new schemes, the framework of the analysis is the same. Following [7], we define the *link state* as the state of a link when a connection request reaches the downstream node of the link. A wavelength channel can be in one of the following three states: (1) free; (2) reserved, yet with no data transmission; and (3) occupied by data transmission. We further denote that a channel is *busy* if it is in state (3); otherwise, it is *idle*.

Let X_j be number of idle wavelength channels on link j, and let $q_j(m)$ be the probability that $X_j = m$. We further assume that when there are m idle wavelength channels on link j, the inter-arrival time of connection requests is exponentially distributed with a parameter $\lambda_j(m)$. Therefore, we have:

$$\begin{cases} q_j(m) &= q_j(0)\cdot\mu^m\cdot\prod_{k=1}^{m}\frac{C-k+1}{\lambda_j(k)}, \quad m=1,2,\cdots C \\ q_j(0) &= \left[1+\sum_{m=1}^{C}\left(\mu^m\cdot\prod_{k=1}^{m}\frac{C-k+1}{\lambda_j(k)}\right)\right]^{-1}. \end{cases} \tag{1}$$

The framework for calculating the steady state probability $q_j(m), j = 1, 2, \cdots, J$ can be summarized as follows:

1) Initiate $\lambda_j(m), j = 1, 2, \cdots, J$ as follows: Let $\lambda_j(0) = 0$ and $\lambda_j(m) = \sum_{R:j\in R}\lambda_R, m = 1, 2, \cdots, C$.
2) Calculate $q_j(m), j = 1, 2, \cdots, J$ through (1).
3) Calculate the blocking probability of R as:

$$B_R = 1-V_R = 1-V_R^F\times V_R^B = 1-(1-B_R^F)\times(1-B_R^B), \tag{2}$$

where V_R denotes the probability that a reservation is successful along the route R, and superscript F and B denote the forward and backward directions, respectively. If, for every route R, B_R has been convergent, then stop; otherwise, go to step 4.

4) Calculate $\lambda_j(m), j = 1, 2, \cdots, J$ as follows:

$$\lambda_j(m) = \sum_{R:j\in R}\lambda_{R,j}(m) \overset{\triangle}{=} \sum_{R:j\in R}\lambda_R\cdot V_{R|X_j=m}, \tag{3}$$

where $\lambda_{R,j}(m)$ denotes the arrival rate of those connection requests for route R which are finally successfully accepted, given that the state of link j is m. Go to step 2.

In the following subsections, we will discuss the calculation of B_R^F, B_R^B and $\lambda_j(m)$, respectively.

B. Blocking in the forward direction

A connection request can successfully reach the destination node if and only if, in all segments of the route, there is at least one available wavelength. Therefore,

$$V_R^F = \prod_{s=1}^{S_R} V_s^F, \tag{4}$$

where S_R denotes the number of segments in the route R. Within each segment, we will continue using the model we developed in [7]. The following steady-state probabilities will be used to calculate the blocking in the forward direction:

- $h_{i,s}$ denotes the probability that a given set of i wavelength channels are free in segment s at the moment when the connection request reaches the downstream end node of the segment.
- $g_{i,j}$ denotes the probability that a given set of i wavelength channels are idle on link j.
- $f_{i,j}$ denotes the conditional probability that a given set of i channels are free on link j, given that these i channels are idle.
- $g_{i,j|i,j'}$ denotes the conditional probability that a given set of i wavelength channels are idle on link j, given that t_j time slots ago they were idle on the $(j-1)$-th link (denoted as link j') of segment s, where t_j denotes the propagation delay on link j.
- $f_{i,j|i,j'}$ denotes the conditional probability that a given set of i wavelength channels are free on link j, given that these i channels are idle and that t_j time slots ago they were free on link j'.

Then we have:

$$V_s^F = \sum_{i=1}^{C}(-1)^{i+1}\binom{C}{i}h_{i,s}, \tag{5}$$

where

$$h_{i,s} = \begin{cases} (g_{i,1}\cdot f_{i,1}), & L_s = 1 \\ (g_{i,1}\cdot f_{i,1})\cdot\prod_{j=2}^{L_s}(g_{i,j|i,j'}\cdot f_{i,j|i,j'}), & L_s > 1, \end{cases} \tag{6}$$

where L_s denotes the hop length of segment s.

Because $g_{i,j}$ and $g_{i,j|i,j'}$ are independent of the propagation delay, they remain the same as those in [7]. The first item that is different in the classic and the new schemes is the conditional probability $f_{i,j}$, which measures the influence of propagation delay. To calculate $f_{i,j}$, we let:

- $\tau_R(j)$ denote the round trip propagation delay between the source node of R and the downstream node of link j.
- $\delta_R(s)$ denote the round trip propagation delay between the downstream end node of segment s and the destination node of R.

We define the *reservation duration*, $t_R^r(j)$, as the duration from the moment that a channel on link j is reserved to the moment that it becomes busy. When the classic DIR is in use, the reservation duration is equal to $\tau_R(j)$ (see Fig. 1). On the other hand, if the IIR scheme is used, this duration becomes $\tau_R(j)+\delta_R(s)$ (see Fig. 2), where s is the segment that includes link j. From the definition of $f_{i,j}$, we have

$$f_{i,j} = \sum_{m=i}^{C} q_{j|i}(m) \prod_{R':j\in R'} \left(1 - A_{R',j}(m, t^{r}_{R'}(j)) \times \frac{i}{m}\right), \tag{7}$$

where R' represents the route of any interfering lightpath; $q_{j|i}(m)$ denotes the probability that m channels are idle on link j given that a specific set of i channels ($i \leq m$) are idle on this link (see [7] for details); and

$$A_{R',j}(m,t) = 1 - e^{-\lambda_{R',j}(m)t} \tag{8}$$

denotes the probability that there is one connection request for R' arriving at link j during time t.

The calculation of $f_{i,j|i,j'}$ is nearly the same as that of $f_{i,j}$ except that $t^{r}_{R'}(j) = 2 \times t_j$ if R' also passes through link j'.

C. Blocking in the backward direction

Similar to the forward blocking analysis, a reservation request is successful if and only if it is successful in all segments. Therefore,

$$V^{B}_{R} = \prod_{s=1}^{S_R} V^{B}_{s}, \tag{9}$$

and

$$V^{B}_{s} = \begin{cases} w_s, & L_s = 1, \\ w_s \times \prod_{j=1}^{L_s - 1} w_{j,j''}, & L_s > 1, \end{cases} \tag{10}$$

where j'' denotes the $(j+1)$-th link of segment s; w_s denotes the probability that the reservation request for route R is *not* blocked at the downstream node of segment s; and $w_{j,j''}$ denotes the probability that R is *not* blocked at j given that j'' is not on the route of the interfering reservation request.

For the IIR scheme, $w_s \equiv 1$ because the vulnerable period is always 0. To calculate $w_{j,j''}$, we first define $t_R(j)$ as the round trip propagation delay between the downstream node of link j and the destination of R. We observe that the reservation for R is blocked at link j if and only if the selected channel was reserved during vulnerable period $t^{v}_{R}(j)$, which equals to $t_R(j) - \delta_R(s)$. Therefore, we have

$$w_{j,j''} = 1 - \sum_{m=1}^{C} q_j(m) \left(1 - w_{j,j''|X_j=m}\right), \tag{11}$$

where $w_{j,j''|X_j=m}$ takes into consideration a condition that $t^{v}_{R}(j)$ time slots ago m channels are idle on link j. Therefore,

$$w_{j,j''|X_j=m} = \prod_{R':j\in R';j''\notin R'} \left(1 - (A_{R',j}(m, t^{v}_{R}(j))) \times \frac{1}{m}\right). \tag{12}$$

For the classic DIR scheme, $w_{j,j''}$ can still be calculated by using (11) and (12) where $t^{v}_{R}(j)$ is replaced by $t_R(j)$. However, the calculation of w_s is quite different. We first observe that a reservation for route R is blocked on the downstream end node of segment s if and only if all channels that were available have been reserved by interfering reservations which arrived during $\delta_R(s)$. Therefore,

$$w_s = 1 - \sum_{m=1}^{C} q_j(m) \left[\sum_{n=1}^{m} v_{s|X_j=m}(n) \times \left(1 - w_{s|m,n}\right)\right], \tag{13}$$

where $v_{s|X_j=m}(n)$ denotes the conditional probability that there are n free wavelengths along the segment s, given that there are m idle channels on link j (here link j denotes the downstream neighbor link of segment s); and $w_{s|m,n}$ denotes the conditional probability that the reservation for R is *not* blocked at the downstream end node of s given that $\delta_R(s)$ time slots ago there were n free channels along s and m idle wavelengths on j. Therefore,

$$v_{s|X_j=m}(n) = \binom{C}{n} \cdot \sum_{i=n}^{m} (-1)^{n+i} \binom{C-n}{i-n} h_{i,s|X_j=m}, \tag{14}$$

where $h_{i,s|X_j=m}$ is a probability similar to $h_{i,s}$, with only an additional condition $X_j = m$. A detailed discussion on this additional condition can be found in [7].

The calculation of $w_{s|m,n}$ is similar to V^{F}_{s} in (5), with C be replaced by n and $h_{i,s}$ be replaced by $u_{i,s|m}$, which denotes the probability that a given set of i channels are free on link j when the reservation arrives given that $\delta_R(s)$ ago m wavelengths were idle on this link. Therefore,

$$u_{i,s|m} = \prod_{R':j\in R'} \left(1 - A_{R',j}(m, \delta_R(s)) \times \frac{i}{m}\right). \tag{15}$$

D. State Dependent Arrival Rate

To complete step (4) of the framework in Section III-A, it remains to obtain the state dependent arrival rate $\lambda_j(m)$. According to (3), we have to obtain $V_{R|X_j=m}$, which can be calculated by using (5) and (10) with parameters $h_{i,s}$, w_s, and $w_{j,j''}$ replaced by $h_{i,s|X_j=m}$, $w_{s|X_j=m}$, and $w_{j,j''|X_j=m}$, respectively. While the first and third terms have been introduced before, $w_{s|X_j=m}$ can be calculated by:

$$w_{s|X_j=m} = 1 - \sum_{n=1}^{m} v_{s|X_j=m}(n) \times \left(1 - w_{s|m,n}\right). \tag{16}$$

IV. NUMERICAL RESULTS

The good blocking performance of the IIR scheme and the high accuracy of the proposed analytical models have been verified by extensive simulation results. Due to limited space, we present only the simulation results for the following Poisson traffic model where

- the traffic pattern is uniform, i.e., the arrival rate of connection requests between each pair of source-destination nodes is identical; and
- the fixed shortest path routing is used between each pair of source-destination nodes.

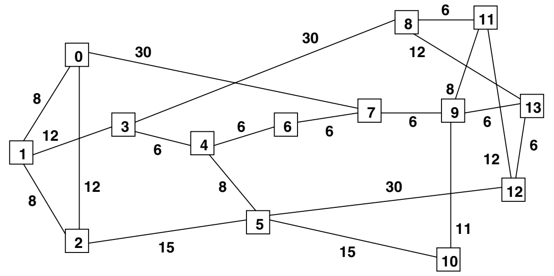

Fig. 3. Network Topology of the NSFNet.

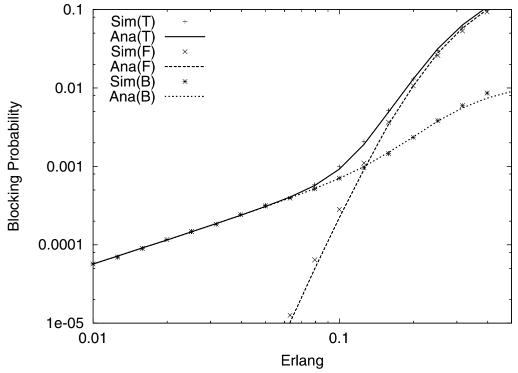

Fig. 4. Blocking of DIR scheme (D=1Sec.)

Our experiments are conducted on the NSFNet topology, shown in Fig. 3, where the numbers on each link denote the physical length in 100s of kilometers. Each link consists of two directional fibers with opposite directions, with eight wavelength channels per fiber. We further assume that wavelength conversion is available on nodes 3, 5, 7 and 9.

In all the figures, the traffic load, measured in Erlang, denotes the normalized traffic load originating from each node; and D ($D = \frac{1}{\mu}$) denotes the average holding time of every connection.

Figures 4 and 5 show the high accuracy of our analytical models for the classic DIR scheme and the IIR scheme, respectively. We observe that, under light traffic load, the blocking primarily takes place in backward direction and is caused by outdated information; whereas under heavy traffic load, the blocking occurs primarily in forward direction, due to insufficient network capacity. We see that our analytical models are highly accurate in analyzing both the forward and the backward blocking probabilities.

Figures 4 and 5 also show that, though the IIR scheme slightly increases the forward blocking, it significantly lowers the backward blocking. As a result, the overall blocking probability is significantly lowered, especially under light traffic load, as we can clearly observe in Fig. 6. Under very heavy traffic load, the forward blocking is dominant, and the blocking probabilities of the two cases is nearly the same. In Fig. 6, we also observe that the proposed scheme performs quite well while under bursty traffic, e.g., when $D = 100$ ms.

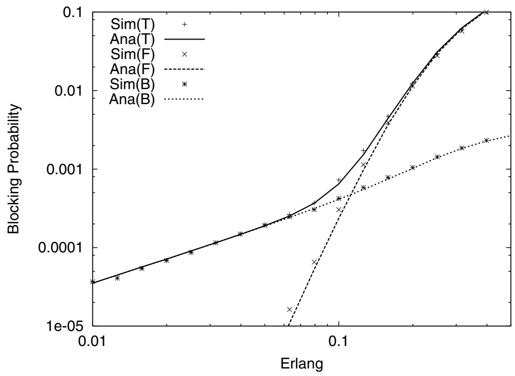

Fig. 5. Blocking of IIR scheme (D=1Sec.)

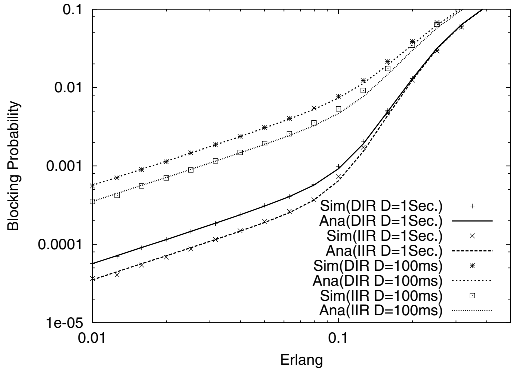

Fig. 6. Performance of DIR vs. IIR

V. CONCLUSION

In this work, we proposed a new signaling scheme for wavelength-routed networks with sparse conversion. Analytical models were developed for evaluating the blocking performance of the new scheme. Analysis and simulation results show that this new signaling scheme can significantly improve the network performance in comparison with the classic DIR method.

REFERENCES

[1] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: a novel approach to high bandwidth optical WANs," *IEEE Trans. Commun.*, vol. 40, no. 7, pp. 1171-1182, July 1992.

[2] P. Ashwood-Smith, *et al.*, "Generalized MPLS: Signaling Function Description," *Internet Draft*, *draft-ietf-mpls-generalized-signalling-07.txt*, Nov. 2001.

[3] X. Yuan, R. Melhem, R. Gupta, Y. Mei, and C. Qiao, "Distributed Control Protocols for Wavelength Reservation and Their Performance Evaluation," *Photonic Network Comm.*, vol. 1, no. 3, pp. 207-218, 1999.

[4] J. M. H. Elmirghani and H. T. Mouftah, "All-Optical Wavelength Conversion: Technologies and Applications in DWDM Networks," *IEEE Comm. Mag.*, March 2000, pp. 86-92.

[5] S. Subramaniam, M. Azizoglu, and A. K. Somani, "All-Optical Networks with Sparse Wavelength Conversion," *IEEE/ACM Trans. Network.*, vol. 4, no. 4, pp. 544-557, August 1996.

[6] J.P. Jue and G. Xiao, "Analysis of Blocking Probability for Connection Management Schemes in Optical Networks," *Proc. IEEE Globecom '01*, San Antonio, TX, vol. 3, pp. 1546-1550, November 2001.

[7] K. Lu, G. Xiao, and I. Chlamtac, "Blocking Analysis of Dynamic Lightpath Establishment in Wavelength-Routed Networks," *Proc. IEEE ICC '02*, New York, NY, vol. 5, pp. 2912-2916, April 2002.