社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE.

フォトニックネットワークにおける分散制御型光パス設定のための波長割当手法の提案と評価

荒川　伸一[†]　　蟹谷　陽介[††]　　村田　正幸[†††]　　北山　研一[††††]

† 大阪大学 大学院経済学研究科 〒 560-0043 大阪府豊中市待兼山町 1-7
††† 大阪大学 大学院工学研究科 〒 565-0871 大阪府吹田市山田丘 2-1
††† 大阪大学 大学院情報科学研究科 〒 565-0871 大阪府吹田市山田丘 1-5
E-mail: †arakawa@econ.osaka-u.ac.jp, ††kanitani@ac.eng.osaka-u.ac.jp, †††murata@ist.osaka-u.ac.jp,
††††kitayama@comm.eng.osaka-u.ac.jp

あらまし　分散制御によりエンドノード間に動的に波長パスを設定する場合、パス設定完了までに送信側から受信側へ経路上の空き波長を調べ、受信側から送信側へ波長予約を行う。分散環境では、この一連のシグナリング動作は各エンドノードで自律的に行われるため、同一のリンクを経由する複数の波長パス設定要求間で、その要求が競合し、波長予約に失敗する可能性がある。特に、波長変換を行わないネットワークにおいては、エンドノード間で同一の波長を予約しなければならないため、エンドノードで選択する波長が他の波長パスによって使用されている可能性が高まる。本稿では、このような分散環境に適した波長選択手法を新たに提案し、既存の手法と比較して低負荷時に棄却率を 1 桁以上向上すること示す。

キーワード　波長分割多重、分散制御、分散光パス設定、波長予約、波長割当

A Wavelength Assignment Method Using a Circular Wavelength–list for Distributed Lightpath Establishment in Photonic Networks

Shin'ichi ARAKAWA[†], Yosuke KANITANI[††], Masayuki MURATA[†††], and Ken-ichi KITAYAMA[††††]

† Graduate School of Economics, Osaka University, 1-7 Machikaneyama, Toyonaka, 560-0043, Japan
††† Graduate School of Engineering, Osaka University,
1-5 Yamadagaoka, Suita, 565-0871, Japan
††† Graduate School of Information Science and Technology, Osaka University,
1-5 Yamadagaoka, Suita, 565-0871, Japan
E-mail: †arakawa@econ.osaka-u.ac.jp, ††kanitani@ac.eng.osaka-u.ac.jp, †††murata@ist.osaka-u.ac.jp,
††††kitayama@comm.eng.osaka-u.ac.jp

Abstract　In a distributed wavelength–routed network, a lightpath request is blocked when its assigned wavelength is already occupied by another lightpath request. Conventional studies assume that a wavelength for the lightpath is selected randomly in the distributed lightpath setup method. However, this random selection method causes unnecessary blocks of lightpath requests, even when the arrival rate of requests is low. In this paper, we develop a novel method for assigning wavelengths, based on the first–fit algorithm. In our proposed method, the intermediate nodes forecast the wavelength that will be selected at the destination node, so that the subsequent lightpath requests avoid the forecasted wavelengths. The forecasted wavelength is thus kept available until the corresponding request reserves it, which prevents wavelength conflicts with other lightpath requests. Computer–simulated performance comparison showed that our method reduces the blocking probability by more than one order of magnitude compared to random selection.

Key words　Wavelength Devision Multiplexing, distributed wavelength reservation, wavelength assignment, blocking probability

1. Introduction

One promising approach to utilize wavelength division multiplexing (WDM) networks effectively is to transfer the data via distributed lightpath establishments. That is, when a data transfer request arises at the source node, a wavelength is dynamically reserved between the source and destination nodes, and a lightpath is configured. After the data transmission finishes using the lightpath, the lightpath is immediately torn down.

Currently, two wavelength reservation methods have been developed to set up the lightpath in a distributed manner [1]. In both methods, the lightpaths are established by exchanging control packets between source and destination nodes. The actual reservation of the link resources is performed while the control packet is traveling from either the source node to the destination node (i.e., in a forward direction), or from the destination node to the source node (i.e., in a backward direction). Several studies have been done on reservation schemes to reduce the blocking probability for lightpath requests [2, 3]. Several algorithms have been proposed for wavelength assignment problem (For example, SPREAD or MAX–SUM algorithms. See details for [4].) However, conventional studies on wavelength assignment problem do not consider the blocking during wavelength reservation process. Without this blocking, how to spread lightpath requests on links is an essential problem for wavelength assignment algorithm.

In a distributed wavelength–routed network, the wavelength selected at a source (or destination) node may already be occupied by other node pairs since the source node does not know when and where other lightpath requests arrive. For the wavelength selection, conventional studies assume that a wavelength for the lightpath is selected randomly in the distributed lightpath setup method [1–3, 5, 6]. However, the random selection in a distributed network causes unnecessary blocks of lightpath requests, even when the arrival rate of requests is low [5,6]. Therefore, a more efficient wavelength assignment method for distributed wavelength–routed networks is needed.

In this paper, we propose a novel wavelength assignment method that is based on the first–fit algorithm to reduce the blocking probability during wavelength reservation process. In this method, wavelengths are put in order of their indexes. This wavelength list can be reordered according to information from the intermediate nodes. The wavelength at the top of the list is selected for lightpath establishment. The intermediate nodes forecast the wavelength that will be selected at the destination node so that the subsequent lightpath requests avoid using the forecasted wavelengths. By doing this, the forecasted wavelength is kept available until the corresponding request reserves it, which prevents wavelength conflicts with other lightpath requests. We used computer simulation to evaluate our method, and confirmed that it can be used to select wavelengths more efficiently (i.e., reduces the blocking probability) than the random selection method.

The rest of the paper is organized as follows. In Section 2, we outline our network architecture and present a new wavelength assignment method. We next evaluate our proposed method by computer simulation in Section 4. Finally, we conclude our paper in Section 5.

2. Wavelength Assignment Method using A Circular Wavelength List

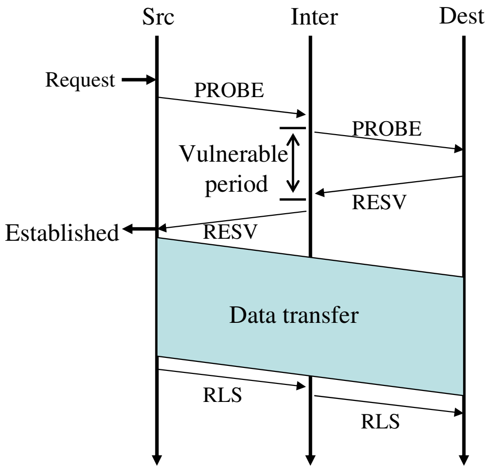
2. 1 Network Architecture

The physical topology of our network model consists of optical cross–connects (OXCs) that are connected by optical fibers. An optical fiber has $W + 1$ wavelength channels: one used as a control channel and the others used as data channels. The control channel carries the control signal (or control packet), and the control packet sets up and/or tears down the lightpath.

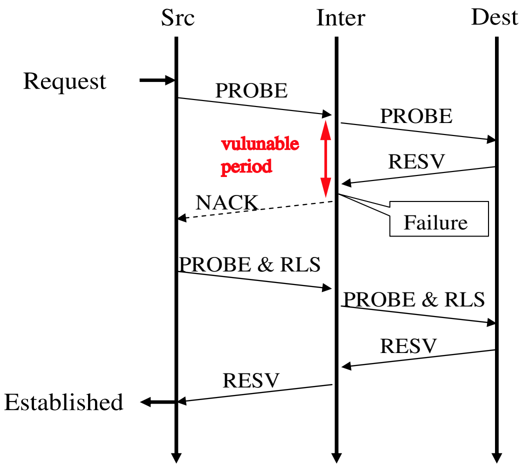
2. 2 Wavelength Reservation Protocol

Since the wavelength assignment is closely related to the wavelength reservation method, we first describe the wavelength reservation method in the distributed wavelength–routed WDM networks.

Unlike centralized networks, distributed networks do not have a central controller. All the nodes in the distributed network have to work autonomously. Therefore, the source and destination nodes do not know which wavelength is available along their corresponding route. The backward reservation [1] solves this problem by using PROBE packets that collect the information on currently available wavelengths along the forward path (Fig. 1(a)). The source node sends a PROBE packet before reserving a wavelength. This PROBE packet collects information on usage of wavelengths along the forward path, but does not reserve wavelengths at this time. Every intermediate node that receives a PROBE packet determines whether each wavelength written in the packet is available in the next link. If a wavelength is unavailable or in use, that wavelength is removed from the available list in the PROBE packet. When the destination node receives the PROBE packet, the destination node knows which wavelength is available along the path, and can choose it. After that, the destination node sends a RESV packet toward the source node. However, even if we use the PROBE–based inspection, a possibility remains of requests being blocked because the information collected by PROBE packets is outdated due to the link propagation delay or processing delay



(a) successful case



(b) fail case

Figure 1 Backward reservation

at each node.

According to K. Lu et al [5] and Arakawa et al. [6], two kinds of blocking have been observed in backward reservation protocol. The first one is blocking in the forward direction (*forward blocking*) due to insufficient network capacity. This kind of blocking occurs when the destination node finds (from the information collected by a PROBE packet) that no wavelength is available between the source and destination nodes. The other one is blocking in the backward direction (*backward blocking*) due to a "vulnerable period" [7] between the PROBE packet passing an intermediate node and the RESV packet reaching that node. In a distributed network, there are propagation delay between nodes and thus the information collected by a PROBE packet may be different from the current link state. The backward blocking occurs when a RESV packet arrives at an intermediate node and the node finds that the selected wavelength has already been reserved by another lightpath request that has arrived earlier. Figure 1(b) shows this instance of reservation failure.

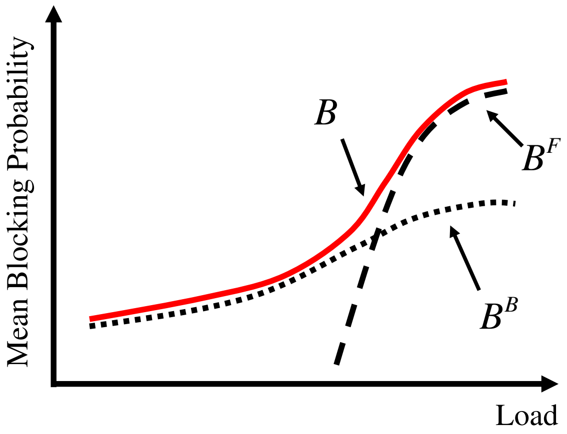


Figure 2 Blocking probability in backward reservation protocol

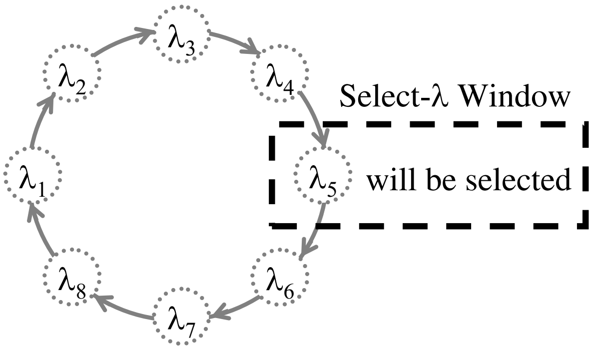


Figure 3 Circular wavelength list (W=8, selected wavelength is λ_5)

According to these observations, we can calculate the blocking probability, B, as:

$$B = B^F + (1 - B^F) \times B^B,$$

where B^F is caused by forward blocking and B^B is caused by backward blocking. Figure 2 indicates an outline of the blocking probability. In the figure, backward blocking makes the blocking probability relatively high even when the traffic load is quite low. We therefore propose a new wavelength assignment method that reduces the backward blocking. The details are described in the next. Note that the forward blocking is inevitable since the wavelength resources are insufficient: only using a wavelength converter or selecting an alternative route would improve the situation.

2.3 Proposal for the Wavelength Assignment Method

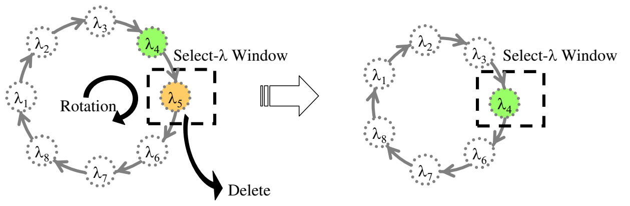
To reduce the backward blocking, we propose a novel wavelength assignment method in which the connection requests generated later avoid the wavelengths that have been selected by the connection requests generated earlier. The features of our proposal are a first–fit–like algorithm adapted to the link state and forecasting wavelengths used for reservation at the intermediate nodes. First, our proposal removes the reservation initiative from the destination node. In the existing methods, the reservation wavelength is selected randomly at the destination node, a process that causes unnecessary blocks. In our proposed method, the wavelength for the reservation is determined automatically based on the link state by which the PROBE packet passed. The destination node has no need to select a wavelength, but only pick up the wavelength from the PROBE packet. Each PROBE packet has a cyclical wavelength list that is arranged in order of wavelength index (i.e., $\lambda_W \rightarrow \lambda_{W-1} \rightarrow \cdots \rightarrow \lambda_2 \rightarrow \lambda_1 \rightarrow \lambda_W \rightarrow \lambda_{W-1} \rightarrow \cdots$). We call it a circular wavelength list (Figure 3). While the PROBE packet travels from source to destination nodes, the circular wavelength list is arranged according to its probed information. When the PROBE packet reaches the destination node, the wavelength at the selection window in the list is selected for the RESV packet. By using the circular wavelength list, it becomes easier to find a wavelength for reservation because calculating the random algorithm at the destination node is unnecessary. Furthermore, the intermediate node can forecast wavelengths that will be selected by incoming PROBE packets.

To forecast which wavelengths will be used, when the intermediate node forwards the PROBE packet, it checks the selection window in the circular wavelength list, and knows which wavelength this PROBE packet will select. After forecasting, the intermediate node writes the result (forecasted wavelength) in its *wavelength forecast table*. A PROBE packet that arrives afterward can refer to the table and know which wavelengths the earlier PROBE packets want to use. At that time, the PROBE packet compares the wavelengths with its own selection window. If the same wavelength is found in its own selection window, the PROBE packet rotates the wavelength list until it finds a different wavelength from those in the wavelength forecast table. By using these circular wavelength lists and forecasting wavelengths, our proposed method can prevent the selected wavelength being reserved by other connection requests. Note that the information of the forecasted wavelength written at each intermediate node is remained until the intermediate node knows that the forecast wavelength is actually reserved, or is not selected at the destination node. This can be achieved by monitoring RESV packets and NACK packets sent from the destination node.

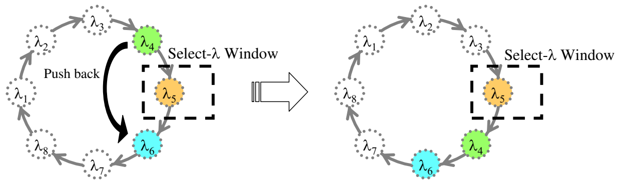
The details of our proposal are described as follows.

（1） Behavior of the source node

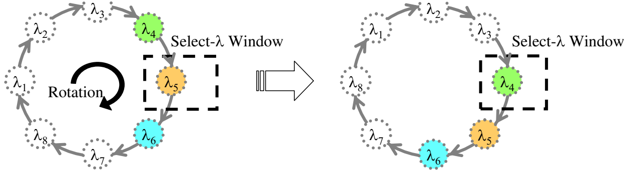
(S1) Receive connection request.
(S2) Create a PROBE packet.
(S3) Check the wavelength availability in the next link.



(a) When the top wavelength is deleted



(b) When the wavelength is set to “undesirable”



(c) When the top wavelength is set to “undesirable”

Figure 4 Update procedures for the wavelength ring

(S4) Determine the initial wavelength of the wavelength ring. Randomly determine the initial wavelength of the wavelength list.
(S5) Forward the PROBE packet.

（2） Behavior of the intermediate node

(I1) Receive the PROBE packet.
(I2) Probe the wavelength availability.
(I3) Check the Wavelength Forecast Table in the previous link and the next link.
- If the forecasted wavelength is found: Set the wavelength “undesirable”.
- Otherwise: Proceed to the next step.

(I4) Update the wavelength ring.
- If a wavelength has been reserved by the other requests: Delete the wavelength from the ring. If the wavelength is at the select–λ window, circulate the ring (Figure 4(a)).
- If a wavelenth is set to “undesirable”: Reorder the ring. Insert the wavelength at bottom of the cyclical list (Figure 4(b)). If the wavelength is at the select–λ window, circulate the ring (Figure 4(c)).
- If the wavelength at the select–λ window has changed:Send update message towards the source node. The update message updates the wavelength forecast table of the intermediate node which the PROBE packet passed through.

(I5) Update the Wavelength Forecast Table by checking the wavelength ring of the packet.
(I6) Forward the PROBE packet toward downstream nodes.

(3) Behavior of the destination node

(D1) Receive the PROBE packet.
(D2) Probe the wavelength availability in the previous link.
(D3) Check the Wavelength Forecast Table.
- If the forecasted wavelength is found: Set the wavelength “undesirable”.
- Otherwise: Proceed to the next step.

(D4) Update the wavelength ring (Same as (I4)).
(D5) Pick up the reservation wavelength that is at the select–λ window in the wavelength ring.
(D6) Return the RESV packet toward the source node.

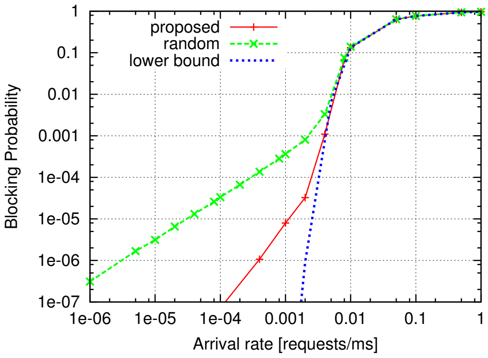
3. Simulation Evaluation

3. 1 Simulation Model

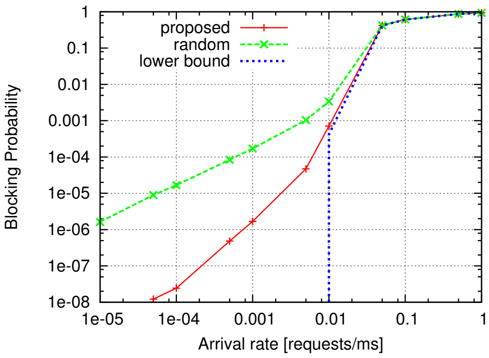
To evaluate the performance of the proposed method, we compared it with random assignment in the backward reservation method. We used the 14–node NSFNET [7] as a simulation topology. The number of wavelengths on each link was set to $W+1$. Each link had the same propagation delay, L_D. The route between a node–pair is prepared by the minimum hop routing algorithm. Data transfer requests arrived according to the Poisson process, and the lightpath holding time was assumed to be exponentially distributed with mean $1/\mu$[ms]. In this simulation, we did not consider the reservation retrial, and we evaluated our proposal in terms of the blocking probability.

3. 2 Results of NSFNET Network

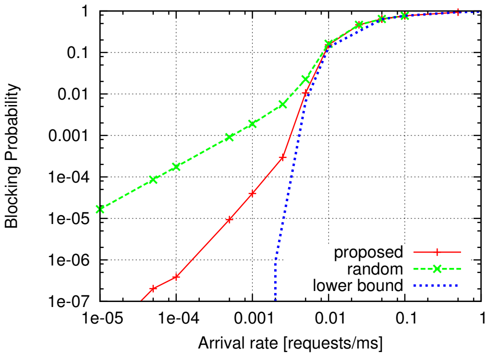
Figure 5(a) shows the result when W=16, $1/\mu$=100ms and L_D=0.1ms. The lower bound is the result when link propagation delay was set to 0 [ms]. Without the link propagation delay, backward blocking did not occur. This figure shows that our proposed method reduces the blocking probability by more than one order of magnitude compared to random selection. In our method, lightpath requests that arrive later can avoid the wavelength that have been selected by earlier requests. Consequently, the selected wavelengths are still available when the RESV packets of earlier requests reach the intermediate nodes. Our proposed assignment method therefore greatly improves the blocking probability when the arrival rate is low. However, compared to the upper bound, backward blocking was still observed. This is because the link propagation delay delayed the update of the wavelength forecast table and the information in the table became outdated. When the wavelength forecast table is out–of–date, the lightpath requests cannot avoid wavelength conflict.



(a) W=16, L_D=0.1ms



(b) W=32, L_D=0.1ms



(c) W=16, L_D=1.0ms

Figure 5 Blocking probability with different paremeters

Figure 5(b) shows the result when W was set to 32. By increasing the number of wavelengths, the performance of the random selection was improved. The performance of our proposed method also improved because in our method, the initial wavelength of the circular wavelength list is selected randomly. Our proposal is very effective regardless of the number of the wavelength.

Figure 5(c) shows the result when L_D was set to 1.0 ms. When the link propagation delay is long, the influence of the backward blocking becomes clearer since the PROBE information is outdated by the long propagation delay. In this case, the update of the wavelength forecast table in our proposed method was also delayed. As a result, the performance of both the random and proposed methods worsened compared to the results in Figure 5(a). However, our proposed method is still effective even when the link propagation delay becomes longer. To see this more clearly, we show the blocking probability dependent on L_D in Figure 6. Here, we set arrival rate 1.0e-06, and the results when W is set to 16 and 32 are presented in the figure. The difference between the random and proposed method is still significant.

When we concentrate on the results of $W = 16$, the result of proposed method show a similar curve with that of random method. However, by comparing the results of $W = 32$ and $W = 16$ for each method, we observe that its difference of proposed method is larger than the difference of random method. The reason is explained as follows. In our method, the blocking, more specifically backward blocking, at a node occur only when the information in the wavelength forecast table at the node became outdated *and* subsequent lightpath request circulates the wavelength–list, and its resulting select–λ window matches the outdated wavelength. As the length of the list increases, the probability that the resulting select–λ window matches to the outdated wavelengths decreases. Thus, the difference becomes large as the number of wavelengths increases in our proposed method.

4. Concluding Remarks

Lightpath establishment consists of routing, wavelength assignment, and wavelength reservation phases. In this paper, we have proposed a novel wavelength assignment method for distributed wavelength–routed WDM networks. In our proposed method, the intermediate node forecasts which wavelength will be selected by the incoming PROBE packet. The result is then communicated to subsequent PROBE packets pass through the node. Owing to this communication of wavelength information, the lightpath requests that pass through the same link can consistently select different wavelengths. We evaluated the blocking probability of our method compared to random assignment. The results confirmed that our proposed method can greatly reduce the reservation blocking when the arrival rate is low.

Some research issues remain. First, in this paper, we have assumed that the routes for lightpaths are predetermined. Although our method can be applied to any routing algorithm, we should evaluate the distributed routing algorithms and clarify which algorithm is suitable for our proposed method. Second, our wavelength assignment method employs a new data structure: a circular wavelength list. This may introduce an additional computational complexity to the intermediate node because the circular wavelength list is updated at every intermediate node. We have to evaluate the control overhead of our method.

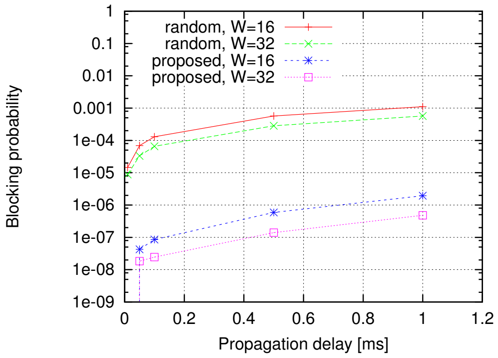


Figure 6 Impact of propagation delay ($1/\mu$=100ms)

Acknowledgement

This work was supported in part by the National Institute of Information and Communications Technology (NICT) in Japan.

References

[1] X. Yuan, R. Gupta, R. Melhem, R. Gupta, Y.Mei, and C. Qiao, "Distributed control protocols for wavelength reservation and their performance evaluation," *Photonic Network Communications*, vol. 1, pp. 207–218, Nov. 1999.

[2] L. Pezoulas, M. J. Francisco, I. Lambadaris, and C. Huang, "Performance analysis of a backward reservation protocol in networks with sparse wavelength conversion," in *Proceedings of IEEE International Conference on Communications*, vol. 2, pp. 1468–1473, May 2003.

[3] F. Feng, X. Zheng, H. Zhang, and Y. Guo, "An efficient distributed control scheme for lightpath establishment in dynamic WDM networks," *Photonic Network Communications*, vol. 7, pp. 5–15, Jan. 2004.

[4] H. Zang and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks," *Optical Network Magazine*, vol. 1, Jan. 2000.

[5] K. Lu, G. Xiao, and I. Chlamtac, "Analysis of blocking probability for distributed lightpath establishment in WDM optical networks," *IEEE/ACM Transactions on Networking*, vol. 13, pp. 187–197, Feb. 2005.

[6] S. Arakawa, K. Miyamoto, and M. Murata, "Performance analyses of wavelength reservation methods for high-speed data transfer in photonic network," in *Proceedings of ITC–CSCC*, pp. 828–831, July 1999.

[7] K. Lu, J. P. Jue, G. Xiao, I. Chlamtac, and T. Ozugur, "Intermediate–node initiated reservation (IIR): A new signaling scheme for wavelength–routed networks," *Journal of Selected Areas in Communications*, vol. 21, pp. 1285–1294, Oct. 2003.