Wavelength assignment scheme for WDM networks with limited-range wavelength converters

Sho Shimizu, Yutaka Arakawa, and Naoaki Yamanaka

Department of Information and Computer Science, Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa, Japan 223-8522

shimizu@yamanaka.ics.keio.ac.jp

RECEIVED 17 FEBRUARY 2006; REVISED 30 MARCH 2006; ACCEPTED 1 APRIL 2006; PUBLISHED 28 APRIL 2006

We propose a new wavelength assignment scheme that improves the blocking probability of WDM networks that use limited-range wavelength converters. Limited-range wavelength converters are attractive for wavelength-routed networks, given current technology, since they offer good utilization of the wavelength resource and improved blocking probability. However, their conversion ranges are limited; the maximum difference between the input and the output wavelengths is restricted. Thus we must take into account the existence of these limited-range wavelength converters. In our proposed scheme, each connection request is assigned a different wavelength according to its hop number. We tend to use different wavelengths for connection requests with different hop numbers. As a result, we can reduce the blocking probability by two decades compared with simply assigning the shortest available wavelengths. In addition, the scheme allows the number of wavelength converters used in each node to be reduced with almost no degradation in blocking probability. Simulation results show that the proposed scheme can reduce the wavelength converters by about 20% on the simple ring network and by 37.5% on the 14-node NSFNet network.

OCIS codes: 060.4250, 060.4510.

1. Introduction

Wavelength-routed networks are attractive for realizing the next generation of wide-area networks, since they offer a data transmission scheme for WDM all-optical networks [1]. In wavelength-routed networks, data is transferred on light paths. A light path is an optical path established between the source node and the destination node. When a connection request arrives, a light path is set up. This involves routing and signaling to reserve a wavelength on each link along the path selected. The benefit of wavelength-routed networks is the ability to more fully utilize the bandwidth of optical fibers, since they do not require processing, buffering, and opto-electronic-optic (O/E/O) conversions at intermediate nodes.

The simplest wavelength-routed networks assign one wavelength to all links of the connection between the source node and the destination node. This requirement is known as the wavelength continuity constraint. The constraint can be avoided by use of wavelength converters at intermediate nodes. A wavelength converter is a device that converts the input wavelength λ_i into a different wavelength, which is then output λ_o. In wavelength-routed networks with wavelength converters, a light path can be established even though there is no common wavelength on all links along the path. This approach can improve the blocking probability and the efficient utilization of wavelengths [2]. The wavelength converters assumed in Ref. [2] provide full-range wavelength conversion capability. This means that any input wavelength can be converted to any output wavelength. While it is possible to realize full-range wavelength converters optoelectronically, such would mean that the networks would lose the benefit of optically transparent wavelength-routed networks. Given current technologies, one of the most popular all-optical wavelength conversion techniques is four-wave mixing (FWM) [3]. In FWM-based wavelength converters the output signal power is significantly degraded as the difference between the input wavelength and the output wavelength increases [4]. Therefore realistic wavelength converters have a limited wavelength conversion capability, and the difference between the input and the output wavelengths is limited. It follows that we need a wavelength assignment scheme that considers the existence of limited-range wavelength converters [5].

Routing and wavelength assignment (RWA) involves very important issues, since it decides the wavelength utilization efficiency and blocking probability. Many papers on routing and wavelength assignment have been published [5–7]. First-fit assignment has been researched as a wavelength assignment scheme for networks with limited-range wavelength converters [4]. Starting with the assumption that all nodes can get global information on all links in the network, first-fit assignment achieves almost the same blocking probability as a network with full-range wavelength converters. Global information about current network resources is effective in reducing the blocking probability, since it allows us to use network resources more efficiently. However, it is not practical to share global information on all links in real time to realize adequate scalability [8]. We need to assign wavelengths in a distributed manner based on information on neighboring links. If the nodes have limited-range wavelength conversion capability, wavelength assignment on a link limits the wavelengths assigned to the other links along the path. For this reason, it is expected that the blocking probability in networks with limited-range wavelength converters will increase compared with networks with full-range wavelength converters.

In this paper we propose a distributed wavelength assignment scheme that considers the number of hops under the existence of limited-range wavelength converters. The concepts of our proposed scheme were presented in Refs. [9, 10]. To allocate different wavelengths as the search area for connection requests with different numbers of hops, the proposed scheme proceeds as follows. The proposed scheme identifies available wavelengths starting from a different initial area according to the number of hops in the request. That is, nodes start the wavelength search from a wavelength closer to the center wavelength when the path has large number of hops. On the other hand, when the request has a small number of hops, the search starts from a wavelength far from the center. This decreases the blocking probability and the number of wavelength conversions needed.

The rest of this paper is organized as follows. Section 2 designates the system model considered in this paper. In Section 3 we propose a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters. Section 4 presents the simulation results of the blocking probability and the average number of wavelength conversions. Finally, in Section 5, we conclude this paper.

2. System Model

2.A. Routing

In this paper we employ simple shortest path routing, in order to focus on the effect of wavelength assignment schemes. We assume that OSPF (open shortest path first) [11] is employed as the routing protocol. Each node exchanges packets describing its own adjacent link states by using OSPF and so obtains the topology of the network. Each node creates the shortest path tree and also knows the number of hops of the paths to all other nodes in the network. Each source node selects the path based on its shortest path tree when a connection arrives.

2.B. Wavelength Reservation Protocol

Figure 1 illustrates an example of the wavelength reservation protocol. In this paper we assume the forward reservation scheme. When a connection request arrives at a source node, the node determines the path used for the light path and sends a RESERVE signal to the next node along the path to reserve a wavelength for the first link, as shown in Fig. 1(a). When an intermediate node receives a RESERVE signal, it sends a RESERVE signal to the next node to reserve a wavelength based on the link state information. When a RESERVE signal reaches the destination node, it sends an ACK signal to the source node, which indicates the success of wavelength reservation on all links. The source node starts to send data after it receives the ACK signal. On completing data transmission, the source node sends a RELEASE signal toward the destination node along the path. A node receiving a RELEASE signal releases the wavelength on the light path used for the data transmission. If there is a link with no wavelength available in a path, wavelength reservation fails. In this case, the node that failed to reserve a wavelength sends a NACK signal toward the source node as shown in Fig. 1(b). Upon receiving the NACK signal, a node releases the wavelength and resends the NACK signal until the NACK signal reaches the source node.

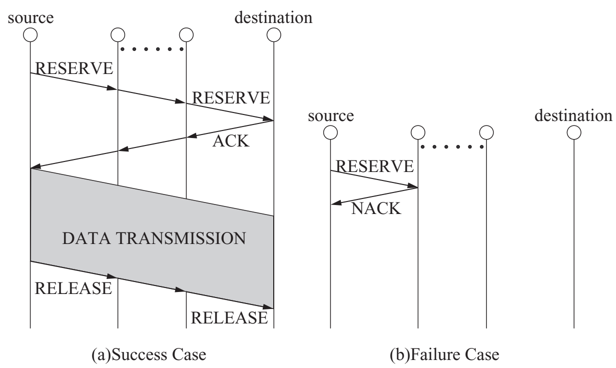


Fig. 1. Forward reservation.

2.C. Limited-Range Wavelength Converter

A major problem of wavelength-routed networks is their inefficient utilization of the wavelength resource and the high blocking probability due to the constraint that the same wavelength must be used on all links along the path. This is known as the wavelength continuity constraint. The solution is the use of wavelength converters. A wavelength converter is a device that can convert the wavelength input to another wavelength that is then output. Full-range wavelength conversion can be achieved optoelectronically [2]. However, this approach loses one key advantage of wavelength-routed networks, optically transparent processing. We assume that this weakness is not acceptable and focus our attention all-optical wavelength converters. Wavelength converters based on FWM are becoming extremely popular [4]. Unfortunately, as shown in Fig. 3, the output signal strength of such a wavelength converter degrades as the difference between the input wavelength and the output wavelength increases. Current technologies restrict the range over which an optical wavelength conversion is possible. The relation between the input wavelength and the output wavelength is modeled as [4]

$$\lambda_{\max(1,i-k)} \leq \lambda_o \leq \lambda_{\min(W,i+k)}, \quad (1)$$

where W wavelengths, λ_1 to λ_W, are multiplexed into an optical fiber, the wavelength conversion range is k, the wavelength input to the wavelength converter is λ_i, and the wavelength output by the wavelength converter is λ_o. Figure 2 illustrates an example where $W = 7$, $k = 1$, and $i = 4$. The output wavelength is limited to λ_3 to λ_5 for input wavelength λ_4.

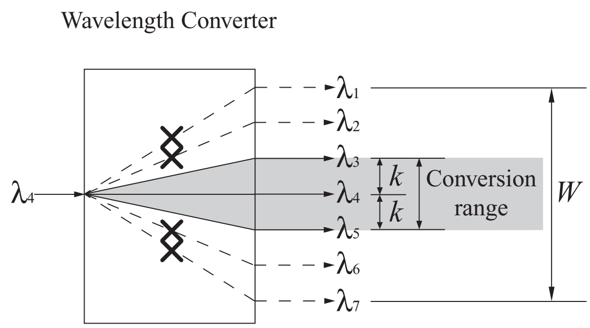


Fig. 2. Limited-range wavelength converter ($W = 7$, $k = 1$, $i = 4$).

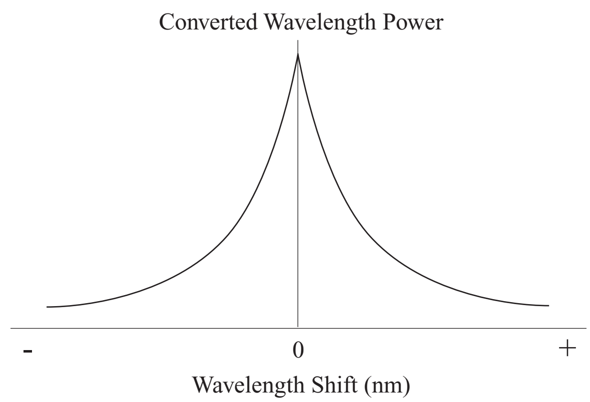


Fig. 3. Converted wavelength signal power model.

2.D. First-Fit Assignment

First-fit assignment has been proposed as a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters [4]. In this scheme the shortest of the available wavelengths is assigned to a new connection request. The behavior of the first-fit assignment in our system model is expressed as follows. A node assigns the shortest wavelength among all available wavelengths to a new connection request when it is a source node. When a node is intermediate node, it assigns the same wavelength assigned to the previous link if the wavelength is available. Otherwise, it assigns the shortest wavelength among other wavelengths limited by Eq. (1). Reference [4] shows that the blocking probability of first-fit assignment is reasonable, but this approach assumes that each node can get the link states of the entire network. If this assumption is incorrect and the states of only the neighboring links are known, the blocking probability degrades dramatically.

3. Proposed Scheme

In this paper we propose a wavelength assignment scheme that considers the number of hops in a connection. The blocking probability can be reduced by the proposed scheme, since the wavelength search area depends on the number of hops in the connection. In the following we denote the number of wavelengths as W, the maximum number of hops in a network as H_{max}, the wavelength conversion range as k, and the number of hops in a connection request as h. Furthermore, we assume that each node knows the maximum number of hops in the network and that it can get adjacent link states. The source node can select any of the wavelengths in the search area, but intermediate nodes must select one the wavelengths that satisfy Eq. (1), where the input wavelength is the wavelength assigned to the previous link. That is, wavelength assignment at the source node differs from that at an intermediate node.

3.A. Wavelength Assignment at the Source Node

We assume that $W = 14$ and $k = 2$. When the input wavelength is λ_1, Equation (1) indicates that three wavelengths are possible, λ_1 to λ_3. When the input wavelength is λ_7, five wavelengths, λ_5 to λ_9, can be output. The number of possible output wavelengths varies with the input wavelength and the conversion range. When the input wavelength is near the center wavelength, the number of possible wavelengths is maximized. In contrast, when the input is distant from the center wavelength, the number is minimized. The necessity of wavelength conversion increases with the number of hops, as does the blocking probability. The goals of our proposed scheme are to reduce the blocking probability and the number of wavelength converters needed. Our approach is to vary the search area of available wavelengths with the number of hops; increasing the number of hops increases the search area. The initial search area is allocated from both ends of the wavelength range. As a result, a connection request with a large number of hops tends to use wavelengths near the center wavelength. If there are vacant wavelengths in the search area, assignment starts from the wavelength nearest the center wavelength, and the first available wavelength is assigned. In this way connection requests that have many hops are more likely to be assigned wavelengths near the center wavelength. Requests with few hops tend to be assigned wavelengths far from the center. This procedure can improve the blocking probability of connections with many hops, which reduces the blocking probability of the entire network as well as the number of wavelength converters needed.

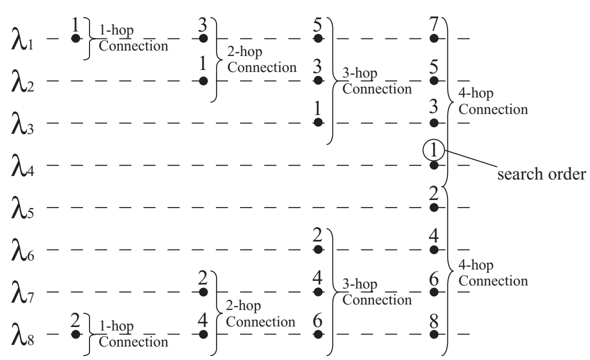


Fig. 4. Search area and search order of the proposed scheme at the source node ($W = 8$, $H_{\text{max}} = 4$).

Figure 4 shows the search area and the search order of our proposed scheme, where $W = 8$ and $H_{\text{max}} = 4$. The numerals in this figure indicate the search order of wavelengths. As shown in Fig. 4, λ_1 and λ_8 are the search area of a one-hop connection. λ_1 to λ_3 and λ_6 to λ_8 are the search areas of a three-hop connection. The search area contains as many wavelengths as there are hops from either end of the wavelength range. This symmetry makes the proposed scheme effective regardless of the number of hops.

3.B. Wavelength Assignment at Intermediate Nodes

The wavelength conversion range follows Eq. (1), where the wavelength assigned to the previous link is λ_i. Figure 5 shows the search order of the proposed scheme at an intermediate node. If available, the input wavelength λ_i is assigned to the next link. Otherwise, we start the search from the wavelength most distant from the center wavelength. Next the node checks the wavelength nearest the center. The first available wavelength is assigned to a connection request. In the example in Fig. 5, the node searches for a wavelength in the order $\lambda_3, \lambda_2, \lambda_1, \lambda_4, \lambda_5$. As a result, fewer wavelengths near the center are selected, which leaves them available for assignment to connections with many hops. Moreover, the number of wavelength conversions for a connection with a large number of hops is also reduced. Consequently, the proposed scheme can reduce the effect of eliminating underutilized wavelength converters.

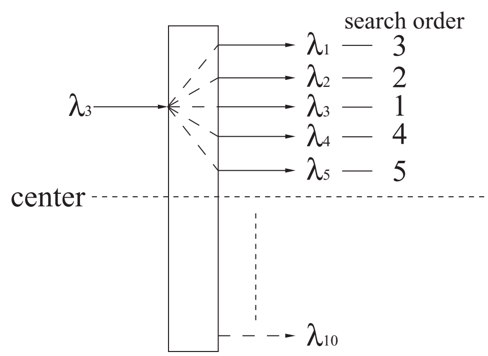


Fig. 5. Search order of the proposed scheme at intermediate nodes ($W = 10$, $k = 2$).

We show an example of the effect of the proposed scheme in Fig. 6. In this figure, we assume that the wavelength conversion range k is two; there are three existing connections between node 4 and node 5. When a new connection request from node 1 to node 8 arrives, in first-fit assignment we assign the shortest available wavelength. Wavelength assignment fails because of the existence of short-hop connections between node 4 and node 5. In contrast, in the proposed scheme, we assign the center wavelength, and the wavelength assignment succeeds. The center wavelength is available for the new connection, and no wavelength conversion is required at intermediate nodes in this example.

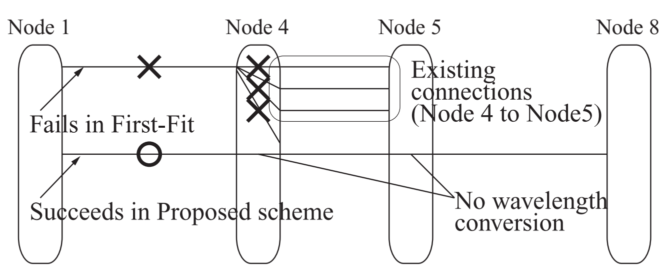
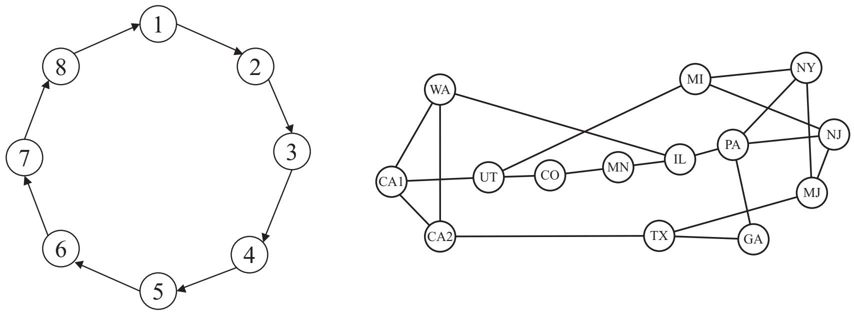


Fig. 6. Effect of the proposed scheme.

4. Performance Evaluation

Computer simulations were conducted to evaluate the blocking probability and the average number of wavelength conversions on the 8-node unidirectional ring network and the

14-node NSFNet network shown in Fig. 7. The number of wavelengths is $W = 14$ in the 8-node unidirectional ring network and $W = 8$ in the 14-node NSFNet network. It is assumed that the connection requests arrive at each node independently following a Poisson process and that source–destination pairs are uniformly distributed. We compared three wavelength assignment schemes: first-fit assignment, random assignment, and the proposed scheme. Random assignment assigns a wavelength from available wavelengths randomly. It should have lower blocking probability than first-fit assignment, since it assigns wavelengths with a uniform distribution, but the number of wavelength conversions is expected to be increased.



(a) 8-node unidirectional ring (b) 14-node NSFNet

Fig. 7. Network topology used in computer simulations.

As the first step in examining the effectiveness of our wavelength assignment proposal, we evaluate the 8-node unidirectional ring network, which is a simple network topology as shown in Fig. 7(a). Figure 8 shows the blocking probability versus the network load on the 8-node unidirectional ring network, where each node has a limited-range wavelength converter. When wavelength converters have limited-range wavelength conversion capability, first-fit assignment greatly increases the blocking probability compared with full-range conversion. The proposed scheme and random assignment better suppress the effect of limited-range wavelength conversion on the blocking probability than does first-fit assignment. If the wavelength conversion range k is large, the blocking probability is decreased. In the following evaluations $k = 1$, which is the strictest case for limited-range wavelength conversion. We see that the proposed scheme and random assignment have almost the same blocking probability. Given the above results, we compared the proposed scheme with random assignment, which has better blocking probability than first-fit assignment.

Next we evaluate the blocking probability on the 14-node NSFNet network shown in Fig. 7(b), which is more representative of real-world networks than a ring network. Figure 9 shows the blocking probability versus the network load on the 14-node NSFNet network. The result indicates a tendency similar to that observed for the 8-node unidirectional ring network. First-fit assignment has higher blocking probability than either the proposed scheme or random assignment, which have almost the same blocking probability. The difference, however, shrinks at high loads. At high loads the proposed scheme has a slightly worse blocking probability than random assignment. The reason for this is that the search area of the proposed scheme for a short hop path is less than that of random assignment. This effect becomes significant only at high loads. We can reduce this effect by combining our proposed wavelength assignment with routing based on global information. In this paper, however, we focus on wavelength assignment schemes. The combination is for future work.

Figures 10 and 11 show the average number of wavelength conversions needed ver-

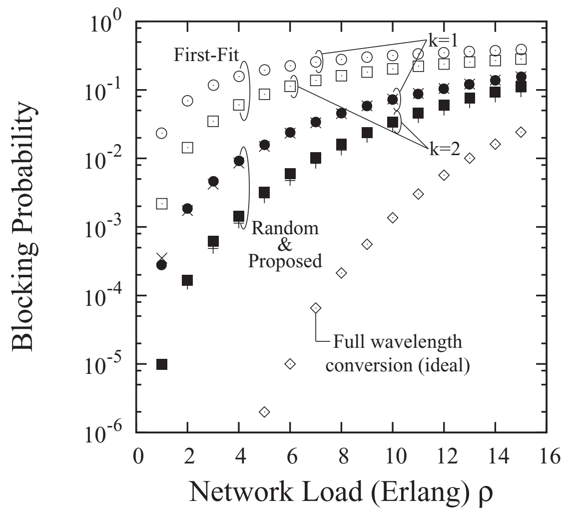


Fig. 8. Blocking probability versus network load ρ on the 8-node unidirectional ring network.

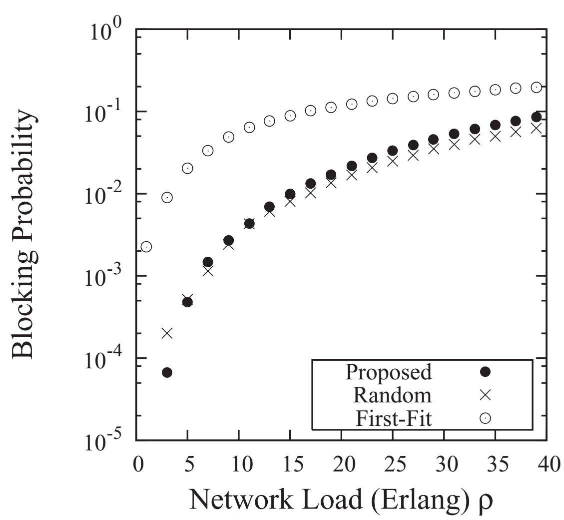


Fig. 9. Blocking probability versus network load ρ on the 14-node NSFNet network.

sus the number of hops. Figure 10 is the result of the 8-node unidirectional ring network, and Fig. 11 is the result of the 14-node NSFNet network. This is done at the network load $\rho = 7.0$ in Fig. 10 and $\rho = 11.0$ in Fig. 11. We assume that each node has sufficient wavelength converters to handle all input wavelengths. The proposed scheme on average requires fewer wavelength conversions than random assignment in both networks. The key point is that the proposed scheme makes it more likely that connections with many hops will undergo fewer wavelength conversions; this suggests that some wavelength converters will be underutilized.

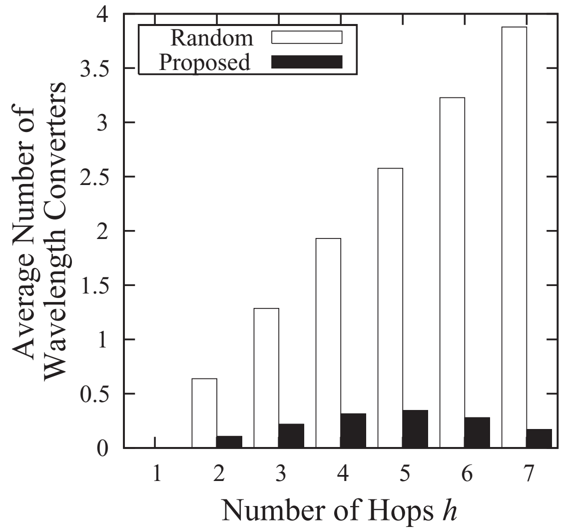


Fig. 10. Average number of wavelength conversions needed versus the number of hops in the 8-node unidirectional ring network ($\rho = 7.0$, $k = 1$).

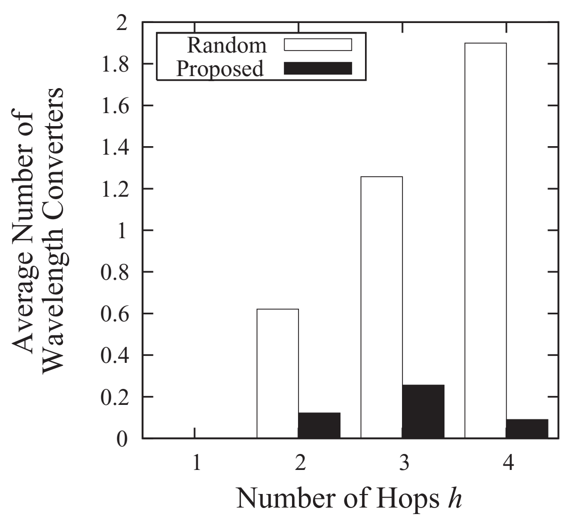


Fig. 11. Average number of wavelength conversions needed versus the number of hops in the 14-node NSFNet network ($\rho = 11.0$, $k = 1$).

Figures 12 and 13 show the blocking probability versus the wavelength converter density on the 8-node unidirectional ring network and the 14-node NSFNet network, respectively. “All” indicates that all nodes have sufficient numbers of limited-range wavelength converters to handle all input wavelengths. “Case 1,” “Case 2,” and “Case 3” represent the situations in which some wavelength converters are eliminated. In the proposed scheme, the utilization of wavelength converters whose input wavelength lies on the side or the center is lower than that of other wavelength converters. There is almost no difference in the blocking probability of the proposed scheme, even though some wavelength converters were eliminated. On the other hand, random assignment allowed the blocking probability to rapidly increase as the number of eliminated wavelength converters was increased. We can eliminate 3 of the 14 wavelength converters in the 8-node unidirectional ring network in ”Case 3” in Fig. 12. This represents an improvement of about 20%. Moreover, we can eliminate three of the eight wavelength converters in the 14-node NSFNet network in ”Case 3” in Fig. 13. This yields an improvement ratio of 37.5%.

	Wavelengths without Converter
Case 1	λ_{14}
Case 2	λ_1, λ_{14}
Case 3	λ_1, λ_8, λ_{14}

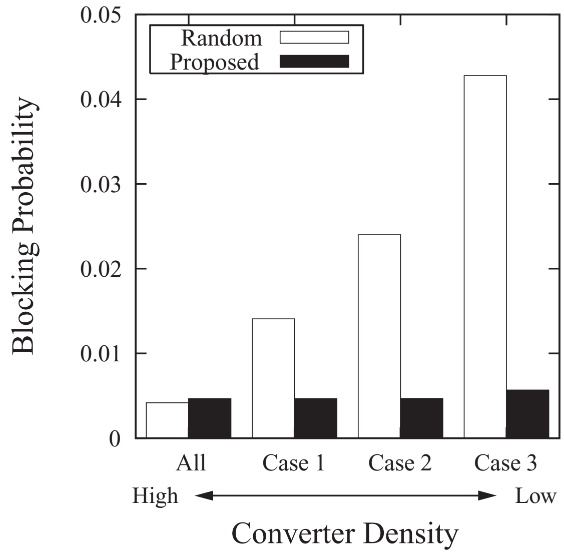


Fig. 12. Blocking probability versus wavelength converter density ($\rho = 3.0$, $k = 1$) in the 8-node unidirectional ring network.

Figure 14 shows the increase in the ratio of the blocking probability versus the network load. We define increase in the ratio of the blocking probability as the ratio of the blocking probability with wavelength converters for all input wavelengths to that with fewer wavelength converters. Eliminated wavelength converters correspond to $\lambda_1, \lambda_8, \lambda_{14}$ in the 8-node unidirectional ring network and $\lambda_1, \lambda_5, \lambda_8$ in the 14-node NSFNet network. It is found that the blocking probability is only slightly degraded in the proposed scheme when underutilized wavelength converters are eliminated. We also observe that the ratio increases less as the network load increases. At high network loads, the blocking probability is also high, regardless of the number of wavelength converters. In this case, the effect on the blocking probability of using fewer wavelength converters is small. The difference in the increasing ratio in the proposed scheme is very small between these two networks, while it is large in random assignment. This shows that the proposed scheme has little dependency on the network topology when the number of wavelength converters is reduced. All of the above

	Wavelengths without Converter
Case 1	λ_8
Case 2	λ_1, λ_8
Case 3	λ_1, λ_5, λ_8

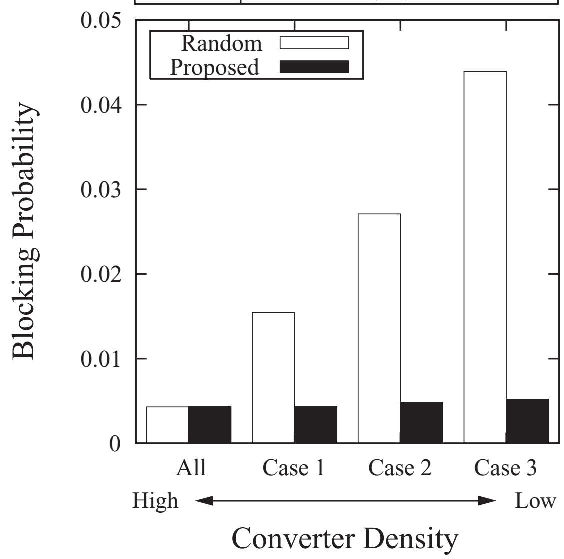


Fig. 13. Blocking probability versus wavelength converter density ($\rho = 11.0$, $k = 1$) in the 14-node NSFNet network.

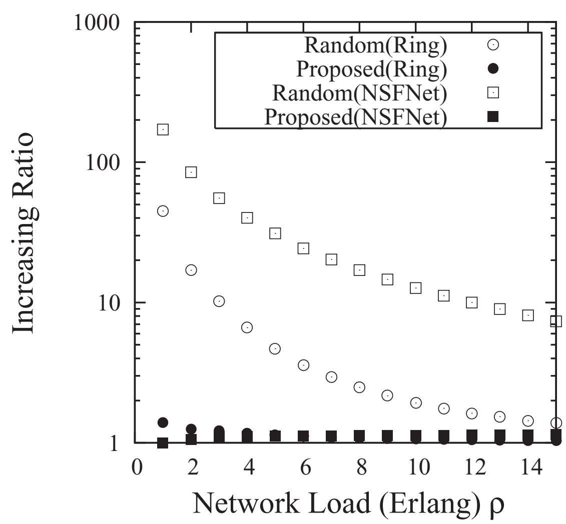


Fig. 14. Increased ratio of blocking probability versus network load when three wavelength converters are eliminated.

results show that the proposed scheme is effective in the simple ring network and also in practical networks such as the NSFNet network.

5. Conclusion

This paper introduced a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters. The proposed method uses a center wavelength for a long hops connection and an edge wavelength for a short hops connection. First-fit assignment does not consider wavelength conversion, and its blocking probability is high. The proposed scheme considers the number of hops in a connection request, and so offers a lower blocking probability than first-fit assignment. Moreover, we showed that it can reduce the number of wavelength converters needed in a simple ring network and in a the realistic network.

Acknowledgments

This work is supported in part by the Keio University 21st Century Center of Excellence program on “Optical and Electronic Devices for Access Networks” and a Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research.

References and Links

[1] I. Chlamtac, A. Ganz, and G. Karmi, “Lightpath communications: an approach to high bandwidth optical WAN’s,” IEEE Trans. Commun. **7**, 1171–1182 (1992).

[2] M. Kovačević, and A. Acampora, “Benefits of wavelength translation in all-optical clear-channel networks,” IEEE J. Sel. Areas Commun. **5**, 868–880 (1996).

[3] J. Zhou, N. Park, K. J. Vahala, M. A. Newkirk, and B. Miller, “Four-wave mixing wavelength conversion efficiency in semiconductor traveling-wave amplifiers measured to 65 nm of wavelength shift,” IEEE Photon. Technol. Lett. **8**, 984–987 (1994).

[4] J. Yates, J. Lacey, D. Everitt, and M. Summerfield, “Limited-range wavelength translation in all-optical networks,” in *Proceedings of IEEE INFOCOM’96* (IEEE, 1996), pp. 954–961.

[5] L. Zhang and L. Li, “Effects of routing and wavelength assignment algorithms on limited-range wavelength conversion in WDM optical networks,” in *Proceedings of IEEE International Conference on Circuits and Systems and West Sino Expositions* (IEEE, 2002), pp. 860–864.

[6] H. Zang, J. P. Jue, and B. Mukherjee, “A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks,” SPIE Opt. Netw. Mag. **1**, 47–60 (2000).

[7] Y. Gong, P. Lee, and W. Gu, “A novel adaptive RWA algorithm in wavelength-routed network,” in *Proceedings of IEEE Conference on Global Telecommunications* (IEEE, 2003), pp. 2580–2584.

[8] C. Assi, Y. Ye, S. Dixit, and M. Ali, “Control and management protocol for survivable optical mesh networks,” IEEE J. Sel. Areas Commun. **11**, 2638–2651 (2003).

[9] S. Shimizu, Y. Arakawa, and N. Yamanaka, “A wavelength assignment considering the number of hops in limited-range wavelength-routed networks,” in *Proceedings of Ninth International Symposium on Contemporary Photonics Technology* (2006), pp. 104–105.

[10] S. Shimizu, Y. Arakawa, and N. Yamanaka, “A wavelength assignment scheme for WDM networks with limited range wavelength converters,” in *Proceedings of IEEE International Conference on Communications* (IEEE, to be published).

[11] J. Moy, “OSPF Version 2,” IETF Request For Comments (RFC) no. 2328 (April 1998).